AD NUMBER
AD881014
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies only; Test and Evaluation; JAN 1971. Other requests shall be referred to Naval Observatory, Washington, DC 20390.**
AUTHORITY
NOBS notice, 9 Feb 1972

AD881014-L

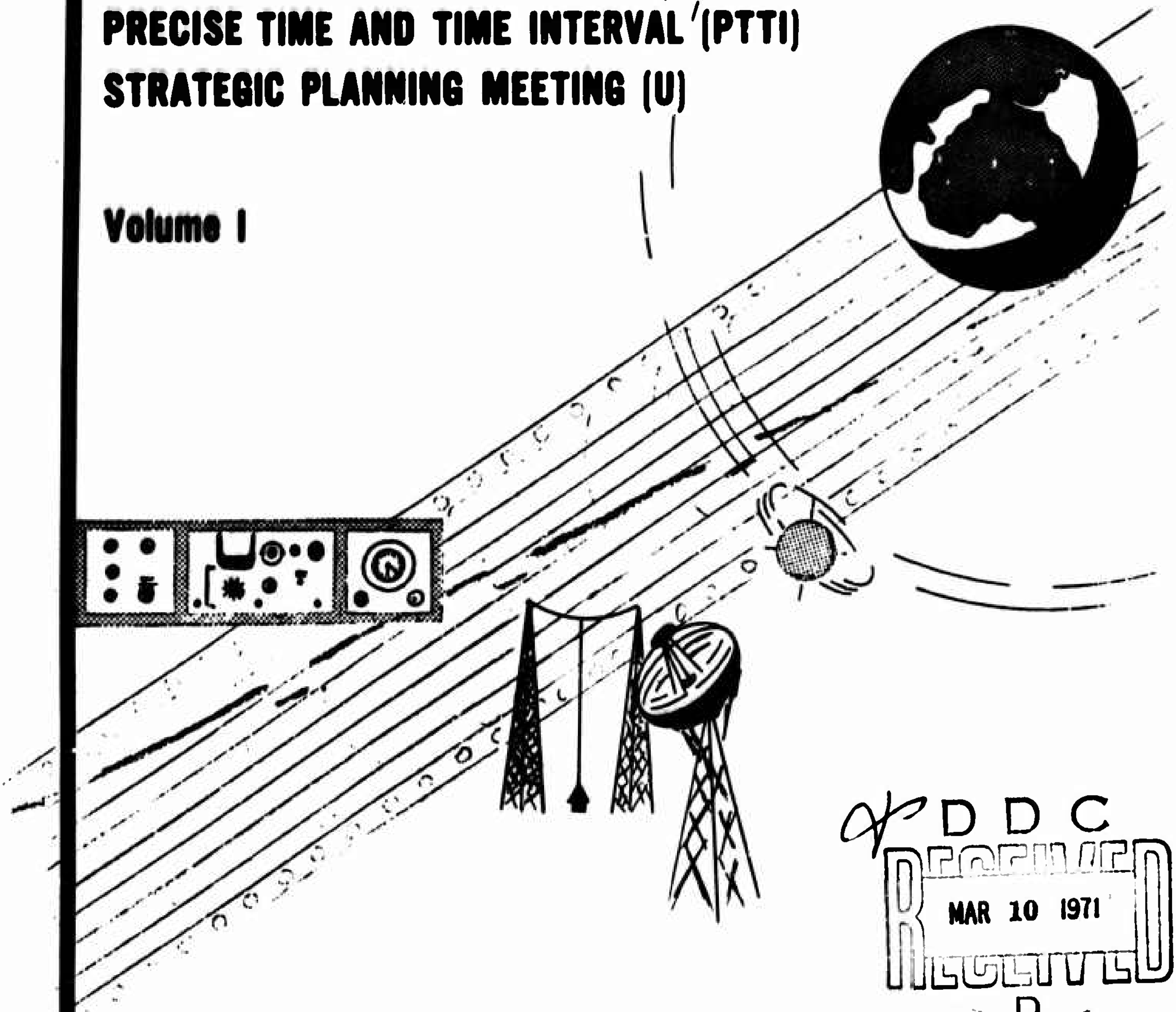
[illegible]

Distribution limited to U.S. Government agencies only.
Reason: TEST + EVALUATION
Date statement applied I JAN 71
Other requests for this document must be referred to:
TECHNICAL OFFICER
U.S. NAVAL OBSERVATORY
WASH. DC 20390

Proceedings from

PRECISE TIME AND TIME INTERVAL (PTTI) STRATEGIC PLANNING MEETING (U)

Volume I



December 10-11, 1970

Best Available Copy

FOREWORD

The Second Department of Defense Precise Time and Time Interval (PTTI) Strategic Planning Meeting sponsored by the Naval Observatory was held December 10-11, 1970 in Washington, D.C., to accomplish the following objectiv ɜs:

- Disseminate information associated with Precise Time and Time Interval dissemination
- Review present and future requirements for Precise Time and Time Interval dissemination
- Review status of current and planned systems for Precise Time and Time Interval dissemination

This report contains a summary of Precise Time and Time Interval topics discussed during the conference. The overall Conference Proceedings are contained in two volumes: Volume I is unclassified for distribution; Volume II is classified SECRET and copies may be obtained by writing the U.S. Naval Observatory, Technical Officer, Washington, D.C. 20390.

Barry M. Atwood

LCDR. Barry M. Atwood
Chairman

TABLE OF CONTENTS

Page

WELCOME
by Dr. L.B. Wetzel 1

INTRODUCTION
by Captain John R. Hankey 3

VLF
by Robert Stone 6

OMEGA NAVIGATION SYSTEM
by L.A. Fletcher 19

A FEW COMMENTS ON OMEGA
by Eric Swanson 30

PRECISE TIME AND TIME INTERVAL (PTTI) DISSEMINATION VIA THE LORAN-C SYSTEM
by Cyrus E. Potts 32

SATELLITE COMMUNICATIONS SYSTEM
by J.A. Murray 55

RECENT VHF/UHF SATELLITE TIMING EXPERIMENTS AT THE NATIONAL BUREAU OF STANDARDS
by G. Kamas and D.W. Hanson 79

621B SATELLITE SYSTEM - ABSTRACT
by Lt.Col. J.A. Fiebelkorn 83

TRANSIT NAVIGATION SATELLITE
by Lauren J. Rueger 84

TIMATION NAVIGATION SATELLITE - ABSTRACT
by Roger L. Easton 108

COMMENTS ON NAVSAT TIME DISTRIBUTION
by Dr. G.M.R. Winkler 109

MOON-BOUNCE TIME SYNCHRONIZATION
by Dr. Walter H. Higa and Samuel C. Ward 111

	Page
TIME DISSEMINATION METHODS FOR NETWORK AND LOCAL TELEVISION - ABSTRACT by George Kamas	119
MICROWAVE, OPTICS, LASERS, AND OTHER EXOTIC SYSTEMS by Robert Stone	120
REQUIREMENTS AND PERFORMANCE FOR TODAY'S ATOMIC STANDARDS by Dr. G.M.R. Winkler	129
EXPLANATION AND REQUIREMENTS FOR UNIVERSAL TIME by Dr. G.M.R. Winkler	152
CONCEPT AND ADVANTAGES FOR PTTI INTEGRATION OF TIME ORDERED SYSTEMS. by Dr. G.M.R. Winkler	156
APPENDIX A: CONFERENCE AGENDA	A-1
APPENDIX B: LIST OF PARTICIPANTS	B-1

WELCOME

Dr. L. B. Wetzel

INTRODUCTION

Captain John R. Hankey

WELCOME

by Dr. L. B. Wetzel*

It is indeed a pleasure to have this opportunity to welcome you to the Naval Research Laboratory (NRL). We are delighted to host this very important conference. For the sake of those of you who are unfamiliar with the Laboratory, I would like to take just a moment to indicate a point of history. NRL opened its doors in 1923 with only two divisions: radio and sound. Nowadays, we call these divisions by more up-to-date titles: Communication Sciences and Acoustics. In the intervening years, specialty laboratories have been added which are grouped into four major areas: Electronics, Materials, General Sciences, and most recently, Oceanology. I am sure that many of you are familiar with the numerous contributions made in each of these areas over nearly 50 years; indeed, we will celebrate our 50th anniversary in another three years, so we have come a long way. Actually, I still occasionally encounter an alumnus of those early days -- someone who might have spent time grinding crystals back in the 1920's for one of the original crystal controlled transmitters which was developed here. Some of our early scientific work -- for example, the development of the transmitter for the Breit-Tuve experiment -- was in the development of crystal controlled equipment.

The interest and deep involvement of NRL in frequency and time -- particularly <u>precise</u> frequency and time -- have extended to the present day. I like to think that our recent developments in the generation and transfer of precise time and time interval, of which you will hear during

*Superintendent, Communications Science Division, Naval Research Laboratory, Washington, D. C., (202) 767-3417.

the conference from Mr. Stone, Mr. Murray, and Mr. Easton, show a healthy persistence of this early innovative spirit. You appear to have a very impressive program outlined and some interesting equipment on display here for the next two days. I am sure you are going to have a very productive meeting. Thank you.

INTRODUCTION

by Captain John R. Hankey, USN*

On behalf of the Naval Observatory, I want to welcome each of you here this morning. In particular, I want to express my appreciation to Dr. Wetzel and to the Naval Research Laboratory for allowing us to utilize their very fine facilities. Our lecture hall at the Naval Observatory is perhaps only one-fourth the size of this one, which is why we are meeting here. Many thanks for your generosity.

I understand that this is the second conference of this type. I did not have the opportunity to attend the last one held about 18 months ago, as I just became Superintendent in September. I must say that the number of people who have honored us by attending this conference impresses me very much; and, since "time is money," I am not going to take up much of yours.

Time is the subject of a good many sayings in our cultural background: "A stitch in time saves nine," "time flies," and, as I just said, "time is money." All of these indicate how important the subject of time is -- even to our ancestors. It is obvious by your attendance that all of you have fully absorbed your cultural heritage, and have seen the importance of time and time interval as it has been expanding in these days of rapid technological progress.

Even before I came to the Naval Observatory, I was aware that time was a major concern. As a navigator, I utilized controlled time ticks to

---

*Superintendent, U. S. Naval Observatory, Washington, D. C., (202) 254-4564.

measure the chronometer's rate which was one of the principle functions of my job when I first went aboard a ship. Now, of course, we are not talking in terms of seconds or even microseconds, but rather in terms of nanoseconds. Dr. G.M.R. Winkler, Director of our Time Service Division at the Naval Observatory, has really kindled my interest in this particular subject. Through conferences such as this, I can learn more about "time." Also, since one of our primary goals is to refine the systems to an optimum state of compatibility, systems managers have an opportunity to become better acquainted with Precise Time and Time Interval techniques.

At present we are engaged in negotiations with the Coast Guard concerning synchronization of additional LORAN-C chains as one aspect of our current work. It is a difficult job, in that Congress authorizes work without appropriating the necessary money. Although the Department of Defense has assigned the responsibility for the determination of Precise Time and Time Interval and its dissemination throughout the Department of Defense to the Naval Observatory, concomitantly, we have received neither additional money nor additional people. It is only through the very fine cooperation we have received from all of you that we have been able to achieve as much as we have, and I want to thank all of you for that assistance.

During the upcoming presentations and the discussions which will follow, we hope there will be a fine free exchange of information. We hope that you will be critical, particularly of us, because we do not exist in a vacuum and the work we do could well be improved. Naturally, we want to do the best job we possibly can in this important role. We solicit your frank criticisms.

Now, as I said previously, "time is money," so I am not going to take up any more of yours. My remarks were designed only to set the stage and to express appreciation to both you and the Naval Research

Laboratory. Many of you have come long distances to be here, and the Laboratory has foregone other uses that it might have had for its facilities in order to accommodate us.

The Naval Observatory, located on Massachusetts Avenue in Northwest Washington, is well worth a visit for those of you who may not have already been there. Besides being a place of some scientific interest, it is a rather pleasant place to visit. In its present location, the Observatory dates back to 1893. Prior to that, in 1844, it was established at 24th and E Streets; and, even prior to that in 1830, it was located downtown just north of the Capitol. So, we have a fairly lengthy history. I think you might find it interesting to visit our present location--now only 70 years old. If you will indicate to LCdr. Barry Atwood or Dr. Winkler a desire to visit the Observatory and have a guided tour, whether day or night, these gentlemen will be glad to arrange one for you.

At this time I would like to turn the meeting over to our technical program. Thank you.

PRESENTATIONS BY

Mr. Robert Stone

Mr. L. A. Fletcher

Mr. Eric Swanson

Mr. Cyrus E. Potts

Mr. J. A. Murray

Mr. George Kamas and Mr. D. W. Hanson

Lt.Col. J. A. Fiebelkorn

VLF

by Robert Stone*

Since 1960 the Navy has employed its high-powered VLF system as a means of rating precision frequency oscillators at remote points. The wavelengths of these frequencies (15 KHz to 35 KHz) are sufficiently long, compared to variations in the length of the propagation path, that phase tracking of the received carrier at remote points, even after several reflections, can be easily accomplished. Atomic standards at the transmitter provide frequency control of better than one part in 10^{11} and permit the rating of oscillators at the received point to better than one part in 10^{10}. Prior to this system, HF radio time signals were employed which had an accuracy of about 1 msec. This system was capable of rating oscillators to about one part in 10^{8} on a day-to-day basis. At the present time, there are seven of these high-powered VLF transmitters as shown in Figure 1. (A recent installation has been made, NDT, in Yosami, Japan.) New antenna systems are being installed in Hawaii and Annapolis. Some of these stations have been operating since the mid-1930's, at which time they employed tuned circuits at the input and intermediate stages. At the present time, all stations have been updated with broadband amplifiers and they employ tuning only at the output/antenna. The newer system greatly simplifies the transmission of time signals.

Operation in the CW mode is quite simple, since all that is required is a precision reference for the carrier. Frequency shift keying (FSK) presents a somewhat more difficult problem. The format used for the VLF

---

*Head, Radio Frequency and Time Station, Naval Research Laboratory, Washington, D.C. (202) 767-3454.

SCHEDULE OF TIME AND FREQUENCY TRANSMISSIONS ON VLF FROM U.S. NAVAL RADIO STATIONS

Station	Location	Frequency (kHz)	Nominal Radiated Power (kw)	Maintenance	Special Transmissions
NAA	Cutler, Maine 44°38!9N, 67°16!9W	17.80	1,000	1400 to 1800 UT each Friday	FSK for two hours followed by CW for one hour. Phase stable on 17.80 but not on 17.85 kHz.
NBA	Balboa, Canal Zone	24.00	150	1200 to 1800 UT each Monday	Time signals on CW Morse from 55 to 60th minute every even hour except 2355 to 2400 UT. FSK continuous at other times. Phase stable on 24.00 but no on 24.05 kHz.
NLK	Jim Creek, Washington 48°12!1N, 121°55!0W	18.60	250	1000 to 1500 UT second Thursday of each month	FSK continuous except five minutes before each even hour on locked key. Phase stable on 18.60 but not on 18.65 kHz.
NPM	Lualualei, Hawaii	23.40	140	1700 UT Monday to 0200 UT Tuesday 1st and 3rd Monday of each month.	FSK continuous. Phase stable on 23.40 but not on 23.45 kHz.*
NSS	Annapolis, Md.	21.40	85	1300 to 1900 UT each Wednesday	Time signals from 55 to 60th minute each hour. CW Morse continuous. Phase stable.
NWC	North West Cape, Australia 21°49!0S, 114°09!8E	22.30	1,000	0000 to 0300 UT each Monday	FSK and CW. Phase stable on 22.30 but not on 22.35 kHz.

FIGURE 1

frequency shift signal is shown in Figure 2. The bandwidths of the antenna systems at these frequencies are narrow and they restrict the speed and magnitude of the carrier shifts. A 50-baud 7.0 teletype code is employed. The bit lengths are 20 msec and the transition time between the stabilized points of the carrier is 2 msec. Fifty cycle carrier shift is employed.

To permit the use of phase-coherent receivers for phase comparison at the remote sites, it is necessary that the carrier being measured be continuous in phase, as shown on the lower portion of Figure 2. Because of the high power involved and the high Q of the antenna system, phase discrepancies at the point of transition will provide transients which result in high voltage flash-overs in the transmitter. Where two carriers are employed, it is necessary that the transition between them occur at a point of phase coincidence. Fortunately, with bit lengths of 20 msec and carrier separation of 50 cycles, phase coincidence will occur at each transition point. However, at the time of the installation of the FSK system, it was not operationally feasible to precisely control the bit lengths; therefore, one of the carriers was controlled in phase to maintain phase coincidence at the transition point and the other carrier was phase-controlled relative to the reference standard. In actual operation, the frequency of the phase-controlled carrier is set at the station assigned frequency and the other carrier is offset 50 cycles either above or below the assigned frequency. At the remote receive end, the on-frequency carrier will be phase-stable except for propagation variations and the offset frequency carrier will contain the small phase variations which were required to compensate for the variation in the timing of the teletype bit stream.

The instrumentation which is now available at all VLF stations is shown in Figure 3. A cesium beam reference standard is used to drive a divider bank which produces the frequencies needed in the synthesizer and also to provide two frequencies, 50 cycles apart, to be used by the

VLF FSK SIGNAL FORMAT

50 Baud	Covered
7.0 Code	50 Cycle Shift

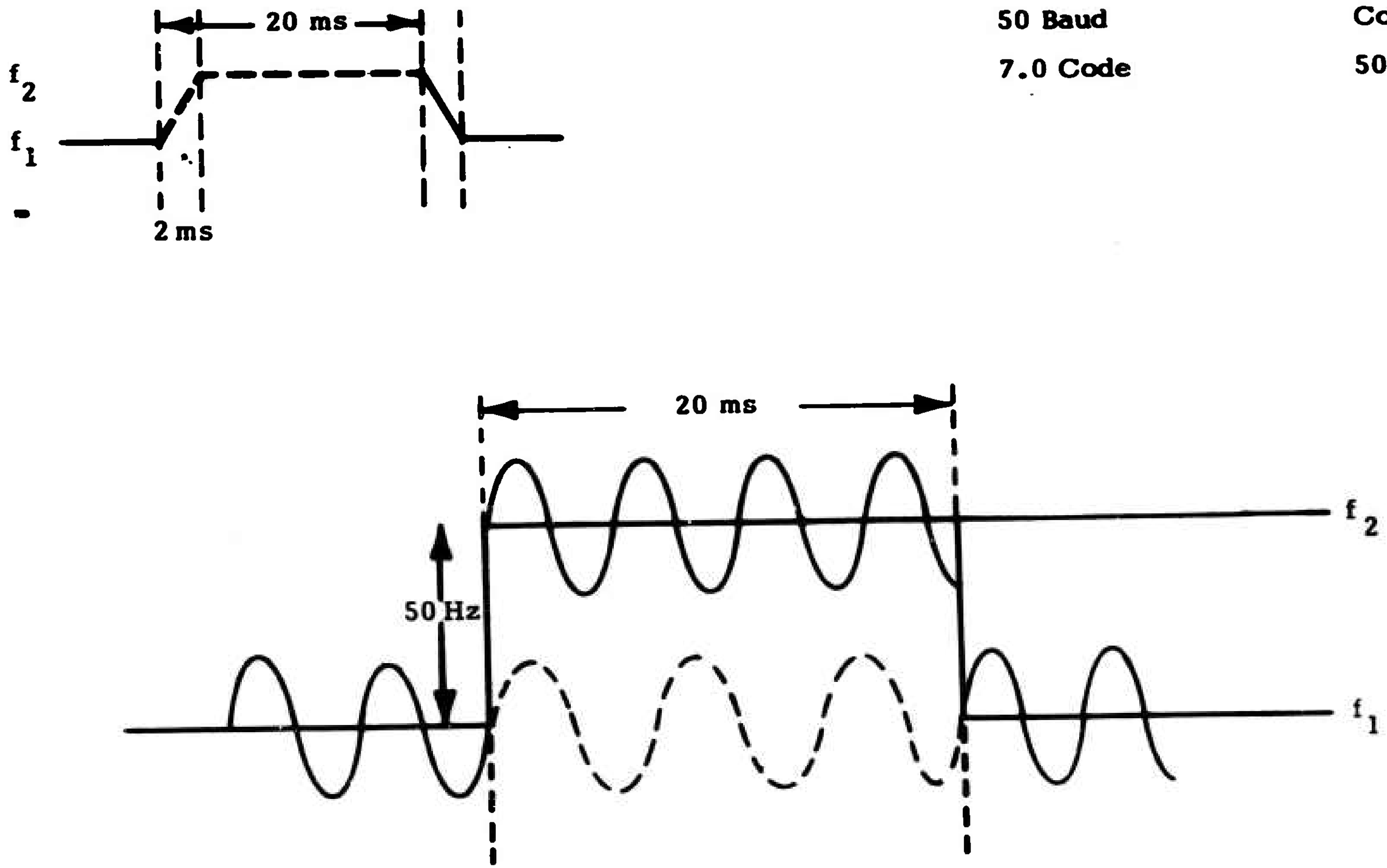


FIGURE 2

PHASE COHERENT FREQUENCY SHIFT KEYING GENERATOR

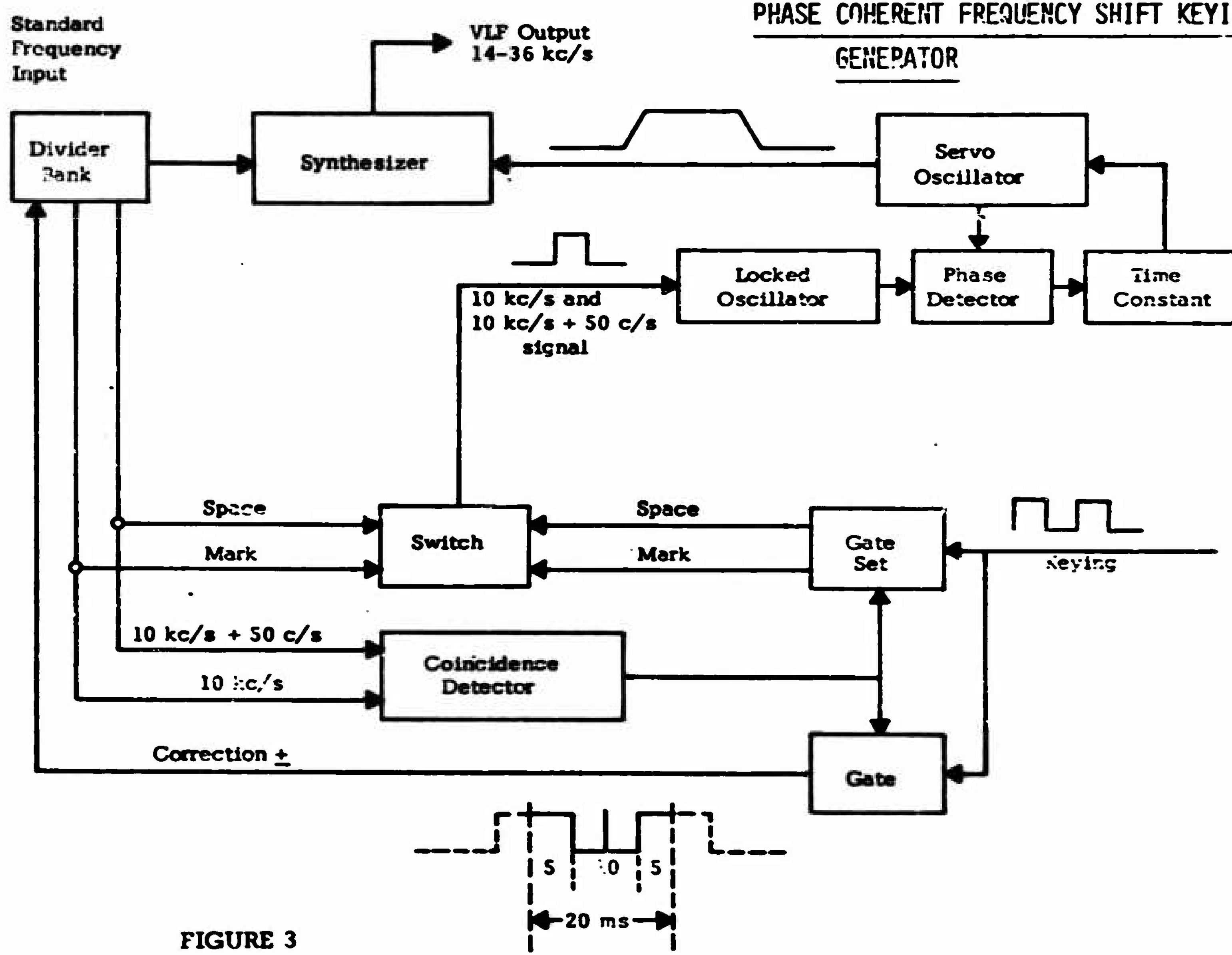


FIGURE 3

keyer. These two frequencies are fed into a switch and also into a coincidence detector. The input key stream sets a gate which is activated by the coincidence pulses. The output of the gate in turn activates the switch in response to the input keying at the phase-coincidence points between the two frequencies. The shifted output from the switch is converted to a sine wave by a locked oscillator and controlled in shift time by the time constant of a servo-controlled oscillator. This output is mixed with the frequencies in the synthesizer to produce the VLF control frequencies of 14 to 36 KHz.

Recently, emphasis has been on controlling the point of transition of the FSK signal at a precise rate and a defined time. A system has been developed and will be put into operation at the Northwest Cape, Australia installation in January 1971. When a communications system is used for precision time and frequency purposes, it is necessary that the communications aspects of the system be preserved. In the case of the VLF system, the teletype code stream carrying the information is generated in a remote classified area and is "covered." Several sources of error must be recognized and compensated for by the system. First, noise bursts sometimes occur on the control line, producing extraneous bits or "hits"; second, at certain times erroneous or non-controlled (that is out-of-time) signals may be imposed on the line; and third, some mistiming may occur between the keying stream and the precision time stream generated from the standard. A block diagram of the storage/retimer portion of the equipment is shown in Figure 4. The first portion of the circuit consisting of a gate, a flip-flop, and a count to 12 is, in effect, a digital low pass filter which must have a count of 12 msec before it will acknowledge a change to MARK or SPACE. This circuitry quite effectively eliminates narrow noise bursts. The second portion of the circuitry, consisting of the phase detector, 2 counts to 14, and a count to 16, recognizes an out-of-time or randomly keyed signal. Fourteen out of sixteen bits must indicate an error in timing for

STORAGE/RETIMER

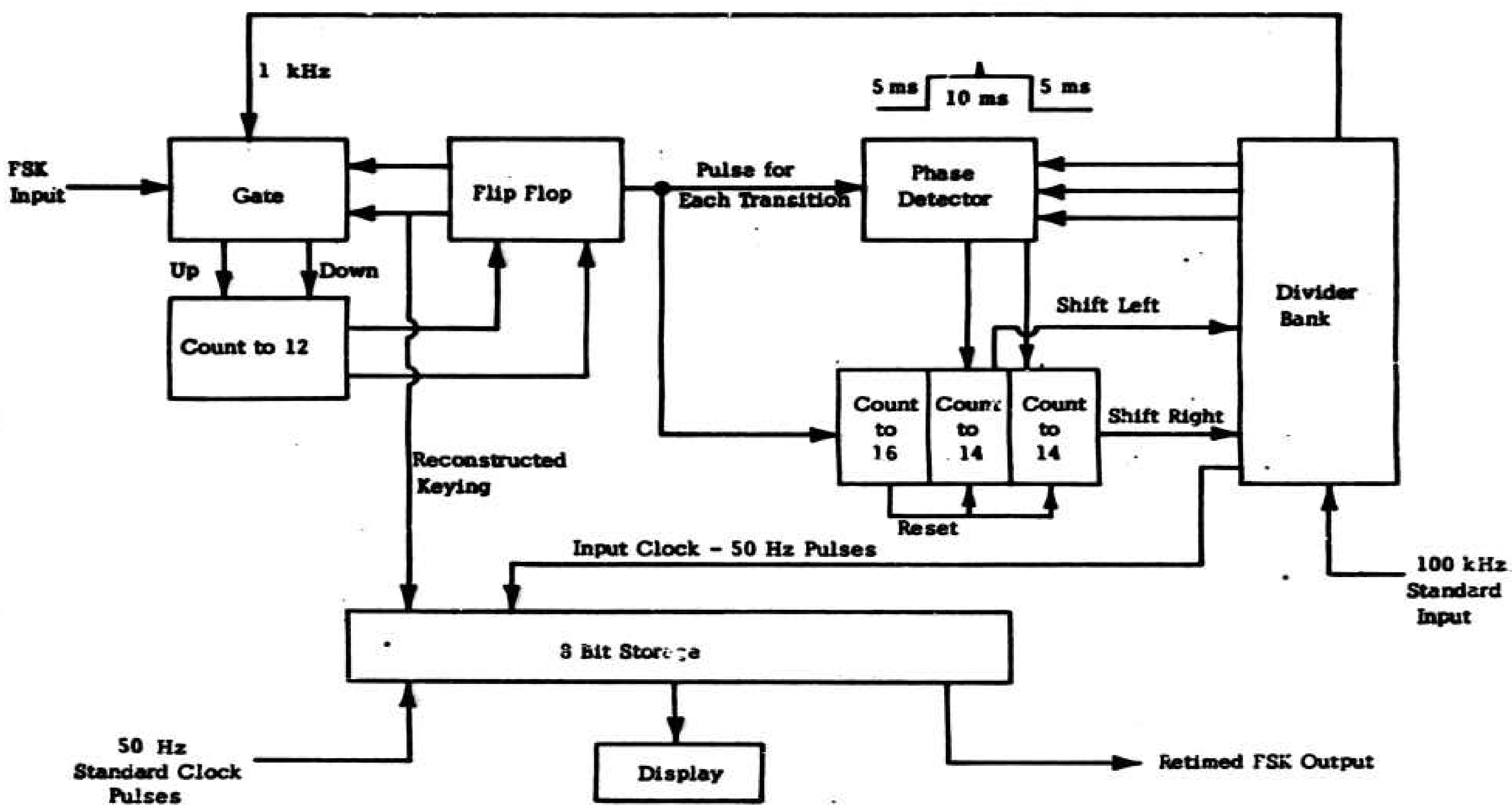


FIGURE 4

the system to recognize and make a timing correction. It is expected that timing errors of several parts in 10^7 may occur between the incoming bit stream and the clock-controlled bit stream. To compensate for this discrepancy, an eight-bit storage has been included. Also, a displav has been provided which will indicate the number of bits in storage. The storage retimer unit is placed in the keying line which drives the FSK keyer.

The use of the storage retimer unit allows the transitions to be set so that the center of the transition is on epoch time relative to the clock at the station. The expected accuracy of this point is about $\pm$ 10 msec as shown on Figure 5. The zero crossing of the positive-going side of the sine wave of the on-frequency carrier is also controlled to within $\pm$ 1 msec, which is about the accuracy one can obtain by a phase recording of the carrier. Identification of the transition to within 10 msec will allow the selection of a particular cycle of the carrier and the identification of the cycle crossover will yield a precision in time of $\pm$ 1 msec. It should also be noted that the phase coincident point between the two carriers will occur at the halfway mark of the transition. This permits the use at the remote received point of a system somewhat similar to that used by the Bureau of Standards, in which an oscillator can be phase-controlled by each of the carriers, then, when mixed together in a coincidence detector, will yield 20-msec markers. No data has been taken to determine the accuracy of this system when propagation anomalies are included; however, the coincident point at the transmitter is controlled to better than $\pm$ 1 msec.

The control of the transition of the FSK will provide time markers at 10-msec intervals throughout the communication; however, for many cases, it is necessary to periodically identify seconds, minutes, and hours. The simplest method of accomplishing this is to periodically send time signals. Figure 6 is a block diagram of the FSK/time signal code keyer. It consists of a series of gates-controlled outputs from a digital

NEW TIME SIGNAL FORMAT

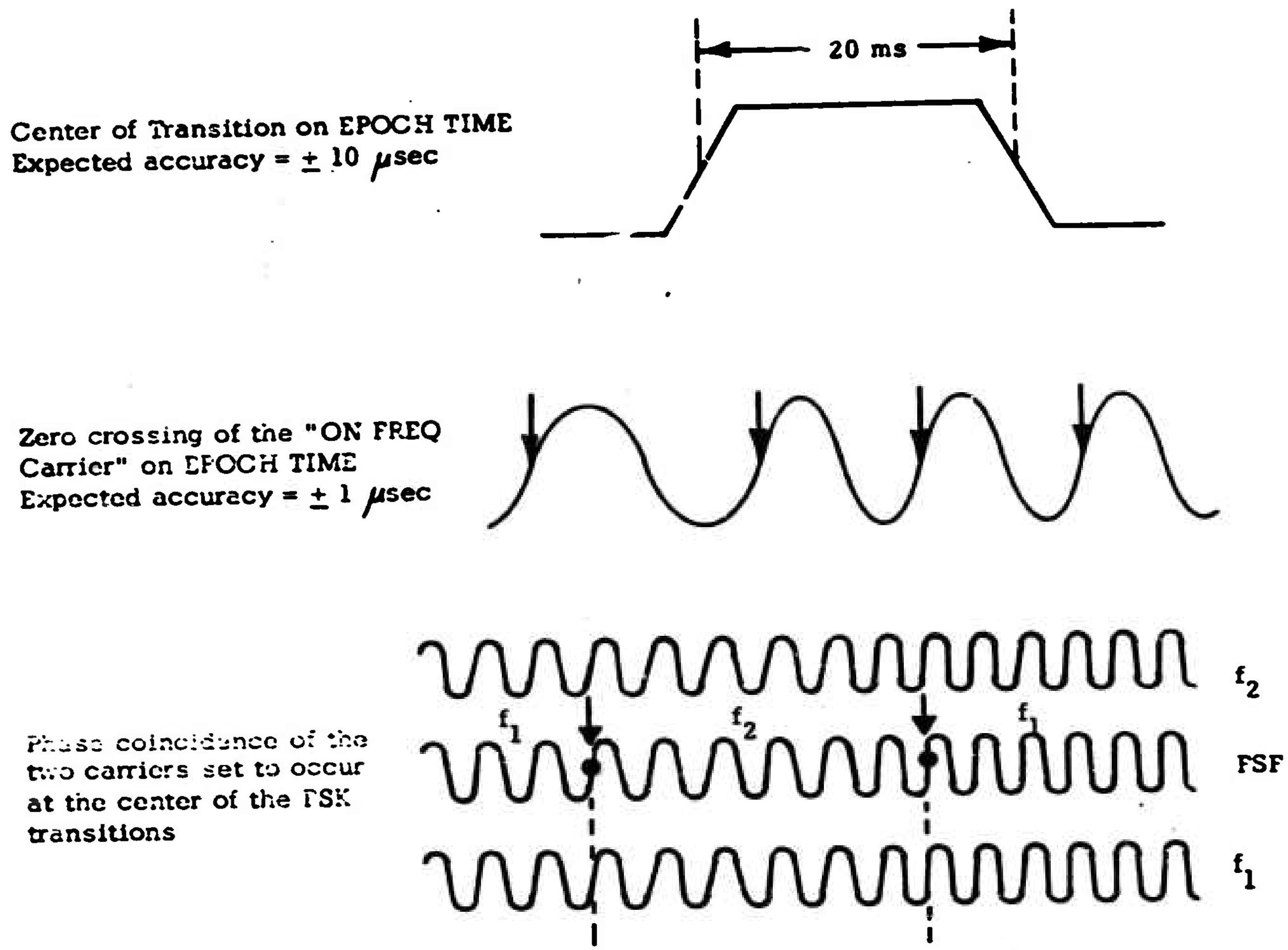


FIGURE 5

FSK/TIME SIGNAL CODE KEYER

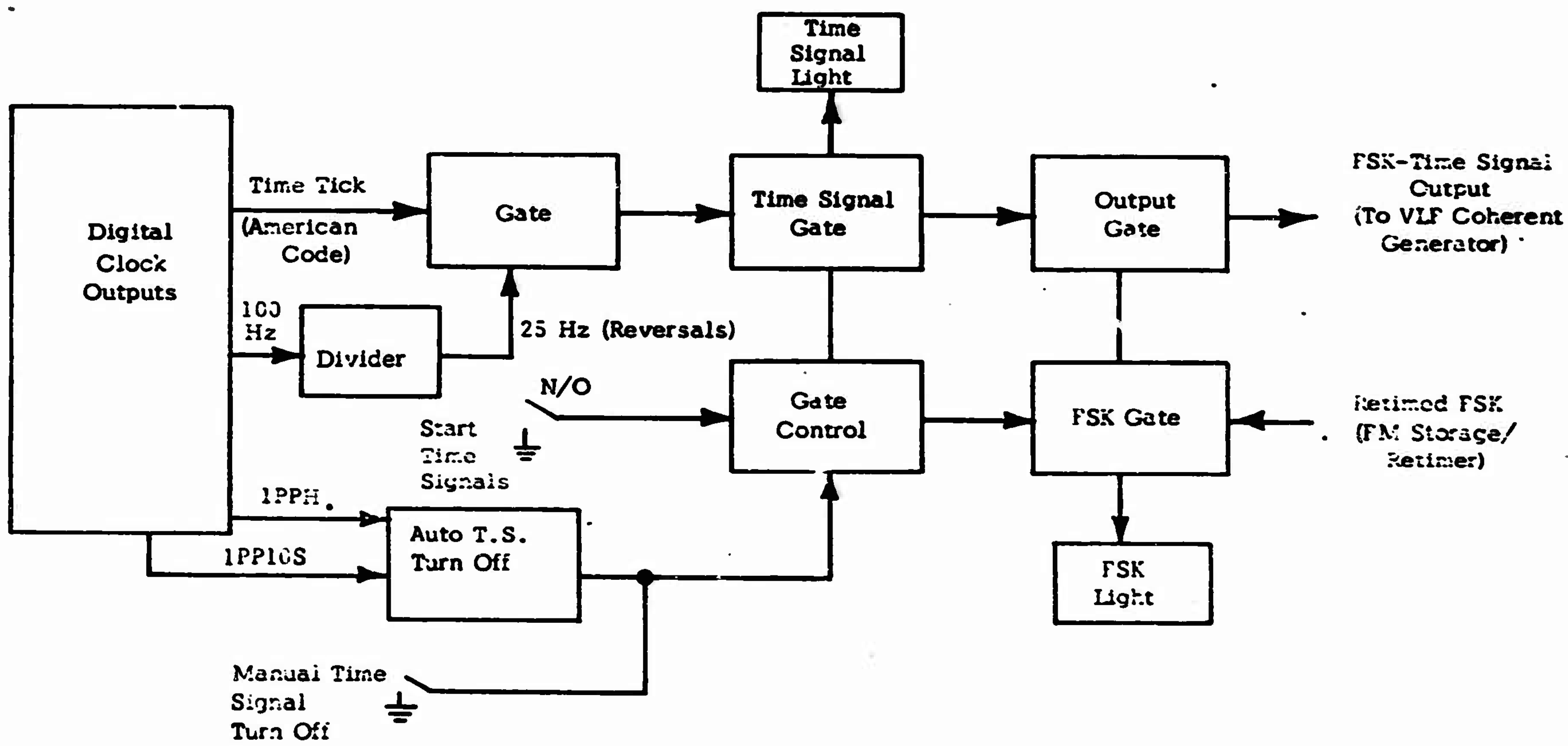
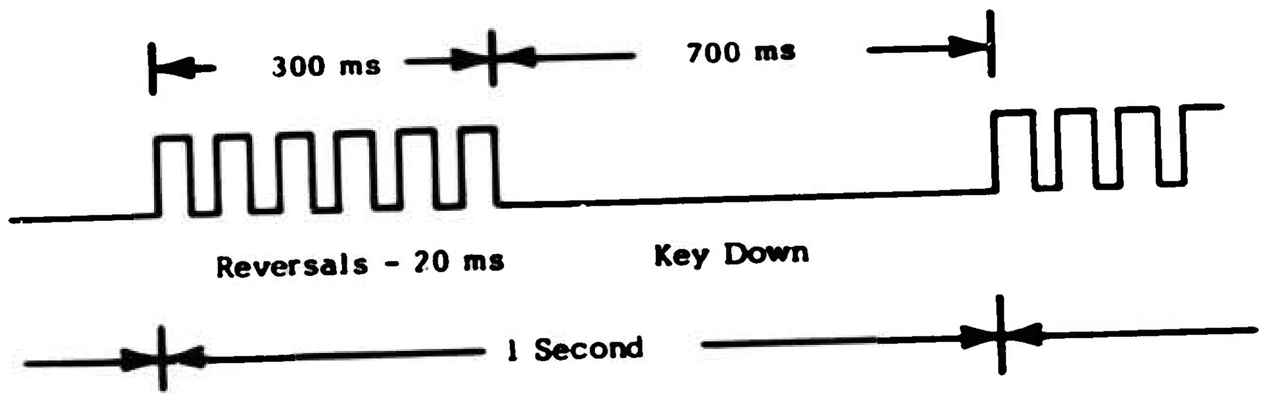


FIGURE 6

clock, such that "time" in the American code can be transmitted when desired. A diagram of the code pulse is shown in Figure 7. The first 300 msec of the code consists of 20-msec reversals, followed by a 700-msec steady signal of the offset carrier. The beginning of the second occurs at the half transition point of the start of the reversals. The time which is produced at the remote receiver is very easily recognized by ear. Present plans in cooperation with the Australian Government are to begin time signals at two minutes before 0430 and 1630 in the NWC transmission.

Figure 8 is the format of the American time code. The 29th second is omitted from every minute, then there are seconds omissions according to the table which indicate the minute for the time mark. The time mark itself is followed by a one-second tone.

TIME CODE VLF



America- Time Code - Begin 2 minutes before 0430 and 1630.

FIGURE 7

TIME CODE FOR U.S. NAVAL RADIO STATIONS (AMERICAN CODE)

Time signals (dashes) are transmitted for each second of the five minute period with the following exceptions:

a. Omit 29th sec/min.

b. Second omissions permit minute identification.

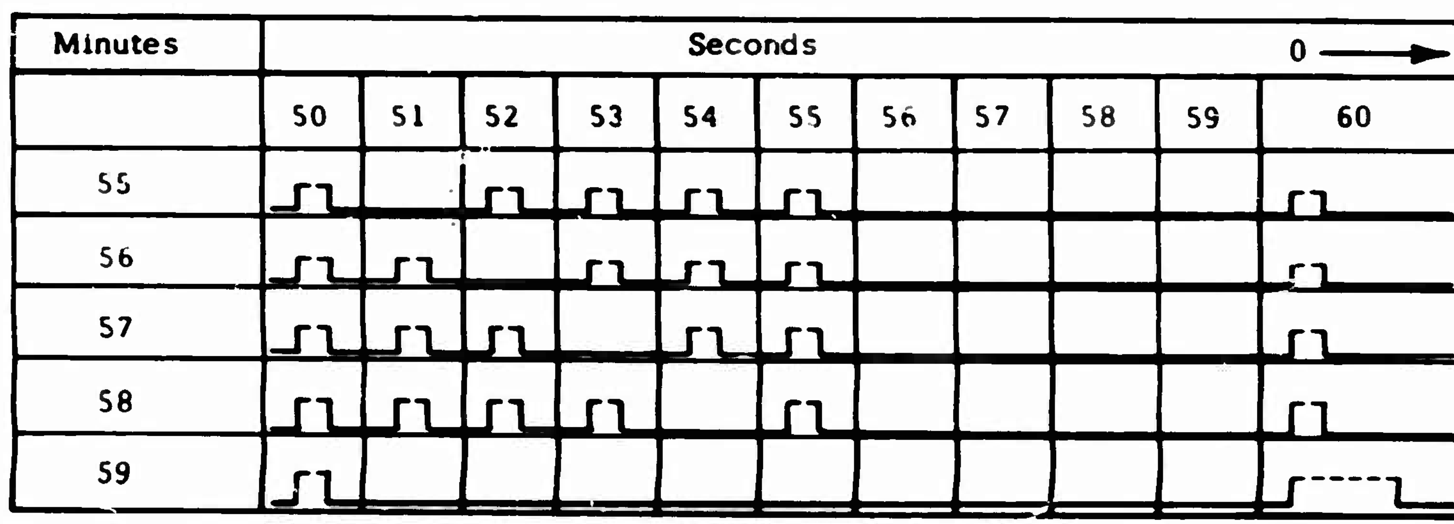


FIGURE 8

OMEGA NAVIGATION SYSTEM

by L. A. Fletcher*

The subject of this paper is precise time and time interval dissemination via the OMEGA Navigation System. Dissemination of time and time interval is an incidental fallout of OMEGA, and this paper will identify the characteristics of the system which give it the ability to disseminate time and time interval.

OMEGA is a very low-frequency navigation system which will, with eight stations, provide worldwide coverage. Figure 1 shows the approximate station locations. The stations located in Norway, New York, Hawaii, and Trinidad are presently in operation (low-power) and the Norway, Hawaii, and Trinidad stations will be upgraded to full-power operation in the final configuration. The New York station will be replaced by a new station presently under construction in North Dakota. These eight stations will be able to provide continuous, all-weather navigation with a one- or two-mile accuracy for user vehicles. At each OMEGA station, the frequency and timing of the transmission are controlled by four cesium beam standards. All eight stations are synchronized to each other so that the epoch for any given station, in comparison to the system's epoch, is generally within 1 μsec. Four stations are currently operating on an interim basis and it has been possible to maintain that synchronization tolerance. Experiments have been performed with the system to see how closely or how easily it can be synchronized to

*Assistant Project Manager for Electronics (PME-119), Naval Electronic Systems Command, Washington, D.C. 20360, (202) OX2-8779.

Observatory time. These experiments indicate that the OMEGA epoch can be held within 5 μsecs of the Observatory epoch without significant effort.

Synchronization of the OMEGA system is presently accomplished as follows. Each station monitors every other station's transmissions and communicates the results back to the control station. The control station then takes these results (numbers) and issues a control message of adjustment to each station. The control communications are presently handled via existing military commercial communication systems; whereas in the implemented system, communication is direct, not via OMEGA frequencies, but by using two additional frequencies in the OMEGA format. This approach will relieve normal communication channels and enhance the reliability and efficiency of OMEGA synchronization control.

Figure 2 shows the anticipated frequency assignment. The Trinidad station, the Hawaii station, and the North Dakota station are the U.S.-owned and operated stations. Frequency assignments have been requested for each of these three stations as shown in the figure. The 10.2, 13.6, and 11.33 KHz are the basic OMEGA frequencies and, as shown for the Trinidad station, the 12.0 and 12.25 KHz will be used to transmit synchronization information between Trinidad and the control station when the system is fully implemented. Some relaying between stations will be required. For example, La Reunion will need to relay its communications data through some other station in order to get to the control station. The planned method of communication is a form of Frequency Shift Keying (FSK) implemented by keying different segment/frequency combinations for each ten-second OMEGA "frame."

It should be reemphasized that Figure 2 depicts a proposed frequency assignment. OMEGA is an international system, and stations that are non-U.S. owned are fully owned and operated by the partner nations and as such, they must request their own frequency assignment. The U.S.

PROPOSED SEGMENT - FREQUENCY ASSIGNMENT (KHz)

STATION \ SEGMENT	A	B	C	D	E	F	G	H
A. NORWAY	10.2	13.6	11.33	12.10	12.10	12.10	12.35	12.35
B. TRINIDAD	12.25	10.2	13.6	11.33	12.0	12.0	12.0	12.25
C. HAWAII	11.80	11.80	10.2	13.6	11.33	11.55	11.55	11.55
D. NORTH DAKOTA	12.85	13.10	13.10	10.2	13.6	11.33	12.85	12.85
E. La REUNION	12.05	12.05	12.30	12.30	10.2	13.6	11.33	12.05
F. S. AMERICA	12.90	12.90	12.90	13.15	13.15	10.2	13.6	11.33
G. S. AUSTRALIA	11.33	12.75	12.75	12.75	13.00	13.00	10.2	13.6
H. JAPAN	13.6	11.33	12.80	12.80	12.80	13.05	13.05	10.2

FIGURE 2

position regarding foreign OMEGA frequency assignments is that of coordinator, and changes may be necessary in the frequencies shown in Figure 2.

With regard to the subject of time and time interval, time interval dissemination is a very obvious fallout from OMEGA. The OMEGA signal is cesium-controlled and can provide a rather excellent method of time interval dissemination worldwide because the system is internally synchronized to within 1 μsec. It can be synchronized without great difficulty to within 5 μsecs of Observatory time. The side frequencies are controlled by the same four cesium standards as the three OMEGA frequencies, and they are unique in that an OMEGA switch or commutator is not required for their use. Precise time can be disseminated by the system, and has been investigated by the U. S. Naval Observatory, NASA, and NBS. The technique involves the use of the two unique frequencies from each station and will be left to other papers presented at this symposium for details.

OMEGA station epoch is defined as the rise time of the 10.2 KHz signal; the 11.33 KHz and the 13.6 KHz signals will be controlled to within $\pm$10 nsecs of the epoch. The side or unique frequencies will be controlled to within $\pm$100 nsec of the epoch and, further, will be controlled to within $\pm$20 nsecs of each other.

As pointed out earlier, OMEGA will use the unique frequencies to communicate the system synchronization data. It is presently anticipated that system synchronization will not require full-time use of the unique frequencies, so there is a possibility that any remaining time may become available at some later date to transmit a time code. With regard to that aspect, the present Navy policy regarding OMEGA is discussed in the following paragraphs.

The Navy is charged with developing OMEGA as a navigation system. The Coast Guard will operate the system and will be the U.S. agent involved in any additional requirement placed on the system. The Navy has no money and no requirement to do more than implement a navigation system. The selection of the unique frequencies has been coordinated with the Observatory, NASA, and NBS to assure, where possible, that OMEGA offers a time disseminating capability. Also, the foreign stations will obviously develop their own policy toward whatever other use besides navigation is made of OMEGA.

Figure 3 shows the present schedule for the OMEGA system. The North Dakota station is now under construction, with about 35 percent of the funds expended on the construction. Buildings are up and the tower will be erected next year. All equipment for all eight stations has been placed under contract, with deliveries to start about January or February of 1971.

OMEGA TRANSMITTER STATION ON-AIR SCHEDULE

NORTH DAKOTA	DECEMBER 1971
NORWAY	JANUARY 1973
JAPAN	APRIL 1973
HAWAII	MAY 1972
LA REUNION	OCTOBER 1973
ARGENTINA	MARCH 1973
AUSTRALIA	MAY 1973
TRINIDAD	NOVEMBER 1973

FIGURE 3

DISCUSSION

Dr. G.M.R. Winkler

I would like to make some supplementary remarks. The Observatory is, of course, interested in assuring that these capabilities which have been explained will be fully utilized and available for dissemination of time. There are a number of problems which have to be solved, the most urgent problem of which is to develop a clear picture of the requirements for the use of the OMEGA system for precise time and time interval dissemination. Another point of uncertainty is the need for a time code. As Mr. Fletcher explained, each station will have five segments which are reserved for unique frequencies, spaced 250 cycles apart. These 250-cycle spacings, and the availability of three additional navigational frequencies which are time-shared, will make it possible to identify a cycle unambiguously at each location with respect to your own clock time. Very simply stated, this is being done by taking advantage of the different durations of one cycle of the two frequencies. If you just consider the two unique frequencies spaced 250 cycles apart, at the moment of emission at the transmitter, they are in phase every 20 msecs because they are multiples of 50 cycles per second. However, as you go out for each cycle, for each wave length you go out away from the transmitter in time and/or space, the difference in periods between these two frequencies is almost one and one-half μsecs -- the exact difference depends upon the frequency. In any event, as you go away in wave lengths from the transmitter, your phase difference increases by about one and one-half μsecs per wave length. This magnitude is large enough to be recognized, and by simply looking at the accumulated phase difference, the knowledge of your distance, and the "electrical" distance from the transmitter (propagation delay is still another problem) you can identify the cycle; you know which

cycle you are on. Once the approximate time is known from the segments timing to within a few milliseconds, you can then, presumably, identify a cycle. As you can imagine, that is not a very simple method, although it can be done. Laboratories have done it successfully, as mentioned by Mr. Fletcher. The laboratories most interested in this kind of cycle identification have been NELC (San Diego); NBS in Boulder, Colorado; and NASA at Goddard. There is a question of how it should be done in practice because it is not a very simple procedure. Any systems used would have to, in my opinion, do that automatically. It would also require a much more extensive prediction of electrical delay, depending upon the solar conditions and the atmospheric conditions between the transmitter and the receiver, than we have available today in order to fully exploit the capabilities in the microsecond range.

Now, again, it can be done and it will be available also to support the primary navigation function of the system by increasing the precision of the fix. The question is: What else would be required to assure the greatest utility of the system? Would there be a need to transmit any time information over and beyond the segment's timing which enables you to identify your clock position within the 10-second interval? Would it be necessary, then, to transmit a time code which would be very slow? Necessarily, the time code could only use the slow segment bit timing or communications capability mentioned by Mr. Fletcher. A complete code cycle, as has been proposed by NBS, would require approximately two minutes. So you would require at least a two-minute sequence; that is, two minutes recording or correlating with an automatic equipment, before you could identify a particular part in your OMEGA sequence, if you did not want to simply listen to a standard time signal.

The code (even if it were on the air) could not possibly be continued 24-hours a day, because in between there is a communication requirement of the system to support the navigation function. The question which

we want to solve, relative to requirement is: Do we need such a time code which would identify not only seconds, but also minutes, hours, and possibly days? The second question is: If any system feels that such a time code would be useful and would be required, what is the minimum amount of time the time code has to be on the air? For instance, would a two-minute period every 30 minutes be sufficient? These are two important questions which we have discussed and which will require a clear definition of requirement. We are very much looking forward to hearing from each one of you who is interested or who foresees a future use of that system for timing purposes.

There are additional questions which have been studied or are being studied by timing advisory group members from each of the agencies previously mentioned as well as from others. These questions concern various antenna and receiver techniques to be used for the extraction of timing information. As you can see, it is possible that for applications on a moving vessel; ship or aircraft, for instance, you would want to have precise time from the same system that provides position. The OMEGA system and the navigation systems generally make it very easy to provide time in a silent one-way mode because they provide proper position and electrical delay from the same system, which also makes the time available. The reason you get both of them is that the signals are redundant. For navigation you receive relative or difference signals simultaneously from several stations which define your geometry. For timing, then, you use one of these signals, but in an absolute way on all frequencies to possibly arrive at your time. At any rate, since it is such a system, it is also possible to obtain time continuously. If that is required, it would mean that navigational receivers, which are under development or testing, would have to be equipped with an additional timing capability to put out a time tick for the vessel's master timing center.

Finally, of greatest concern to us is the actual usefulness of such a system for the dissemination of time. It would be necessary to know much more, as I mentioned before, about the exact propagation characteristics. One would have to be able with either the help of tables or of mathematical models to compute a momentary electromagnetic distance in terms of wave length from the transmitter to your receiver in order to make fast-timing information available to you with the precision approaching 1 μsec.

I would like to close by asking you again to make your ideas or requirements known to the Observatory.

A FEW COMMENTS ON OMEGA

by Eric Swanson*

First, I would just like to reiterate Mr. Fletcher's comments concerning the synchronization of OMEGA to the international time base, as specified by the Naval Observatory master clock. This is being done and, in fact, OMEGA has been running better than the 5 μsecs which Mr. Fletcher mentioned. It is being done mainly for our own convenience. Ironically, it is easier to hold OMEGA to the Observatory clock than not to synchronize it.

The second point I would like to mention is that we have looked at the VLF timing capability recently for NASA using OMEGA, and I have a nice thick report for anyone who has the heart to read it. It shows that many sites can, indeed, come out somewhere between 1 and 10 μsecs, depending upon how you want to look at it. You back off to something like a typical ten; this is the sort of thing that you can do continuously, and for which, in fact, you do not need an elaborate standard. As you try and go down, of course, you are going to require a better and better clock. It occurs to me that this is two or three orders better than the standard which the fleet is using for timing today, and I cannot help thinking that there is a useful capability here, especially since it can be used on the high seas and since it is a navigation system.

The final point to mention is the intersynchronizing of OMEGA stations to each other and/or to the Naval Observatory for the past four

---

*Naval Electronic Laboratory Center, San Diego, California, (714) 225-6365.

or five years. In fact, we typically hold 1 μsec or so with respect to each other on an international basis, and have been doing so for years. In attempting to do this, I think we have perhaps made every mistake possible. There is a control problem quite distinct from the time dissemination problem. One must have a good clock and, at the same time, good information. The dynamics, especially with an interrelated system of eight stations, are indeed complex. This is an appeal. We know a little about what we are doing here, and if anyone has looked in any detail at an interrelated control problem, I would welcome their comments. I feel also that some other systems may have similar requirements. If they do, I would again like to coordinate with them.

PRECISE TIME AND TIME INTERVAL (PTTI) DISSEMINATION VIA THE LORAN-C SYSTEM

by Cyrus E. Potts*

INTRODUCTION

During the last decade the rapid growth of time/frequency technology has brought forth various requirements which have, in some cases, exceeded the capabilities of the available services. Consequently, many new schemes have been proposed, and some implemented, to transfer time and time interval from one geographic location to another. These schemes vary from the physical transportation of precision standards and clocks, to the utilization of electromagnetic emissions from ground-based as well as airborne and earth satellite sources. For economic reasons most of the latter schemes involve the piggybacking of the time service on existing or proposed communications, navigation, or other types of systems. This paper describes PTTI dissemination on one such system, the LORAN-C navigation system. Emphasis is placed on those advantageous characteristics which are of the greatest interest to potential users while at the same time equal time is given to system limitations. At this point in time/frequency technology growth, there is no single system which is a panacea for PTTI user requirements.

BACKGROUND

The LORAN-C Navigation System was conceived as, and primarily serves as, a long-range precision hyperbolic navigation system which

---

*Lieutenant Commander, USCG, U. S Coast Guard Headquarters, Washington, D.C., (202) 426-1195.

typically offers users several hundred feet position accuracy at ranges in excess of 1000 nautical miles.[1] However, in recent years improvements to the system have resulted in increased reliability and accuracy and have offered a modem for ancillary uses including range-range mode navigation[2] (both intra- and inter-chain), communications, and PTTI. The ability of the system to be utilized for dissemination of PTTI derives from the excellent long-term stability of the atomic frequency which are used to control the emissions from the individual LORAN-C stations. Cesium beam frequency standards are installed at all LORAN-C stations and provide the fundamental source of timing necessary for both the navigation and PTTI functions. By setting the frequency of the standards to a convenient scale, currently Universal Coordinated Time (UTC), the emissions themselves become a reliable frequency reference, and the pulsed format allows the recovery of epoch information. Since a common frequency source is used at each station, the pulse interval and carrier phase information are coherent.

The LORAN rates assigned to the individual LORAN-C chains serve to identify the transmissions of one chain from another, eliminate mutual interference, and optimize the signal-to-noise ratio for the particular chain geographic configuration. The transmissions are in the form of groups of nine pulses from the master station and eight from the slave station. The leading edge of the transmitted pulse envelope can be approximated by the expression $e(t) = t^2 \epsilon^{-at}$, where α is chosen to maximize the expression for t equal to 65-70 μsecs. Figure 1 illustrates the normalized ideal LORAN-C pulse leading edge for two values of α. By definition, the start of the LORAN-C pulse is that point which precedes the third to fourth RF cycle zero crossing by 30 μsecs. This third to fourth cycle zero crossing is also the normal receiver phase tracking point, since it usually yields the maximum signal-to-noise ratio without skywave contamination. Phase coding of the individual

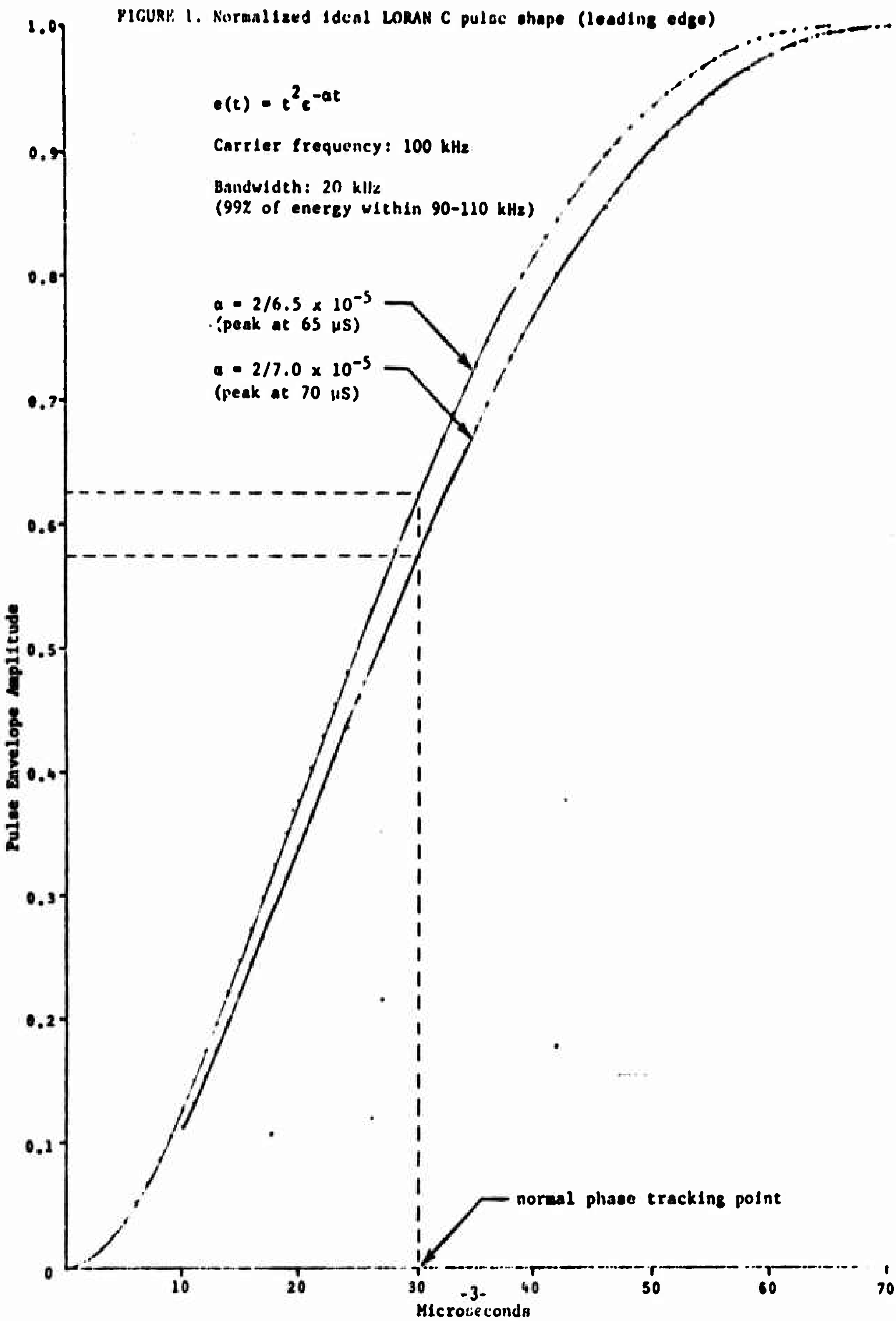


FIGURE 1. Normalized ideal LORAN C pulse shape (leading edge)
$e(t) = t^2 \epsilon^{-at}$
Carrier frequency: 100 kHz
Bandwidth: 20 kHz
(99% of energy within 90-110 kHz)
$a = 2/6.5 \times 10^{-5}$
(peak at 65 μS)
$a = 2/7.0 \times 10^{-5}$
(peak at 70 μS)
normal phase tracking point
Pulse Envelope Amplitude
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10
20
30
40
50
60
70
Microseconds
-3-

FIGURE 1

pulses within a pulse group is employed to reduce skywave and other interference. Positive phase code means the first RF cycle starts in a positive direction. Negative phase code is 180° in opposition to positive phase code. The pulse group format and phase code format are illustrated in Figure 2.

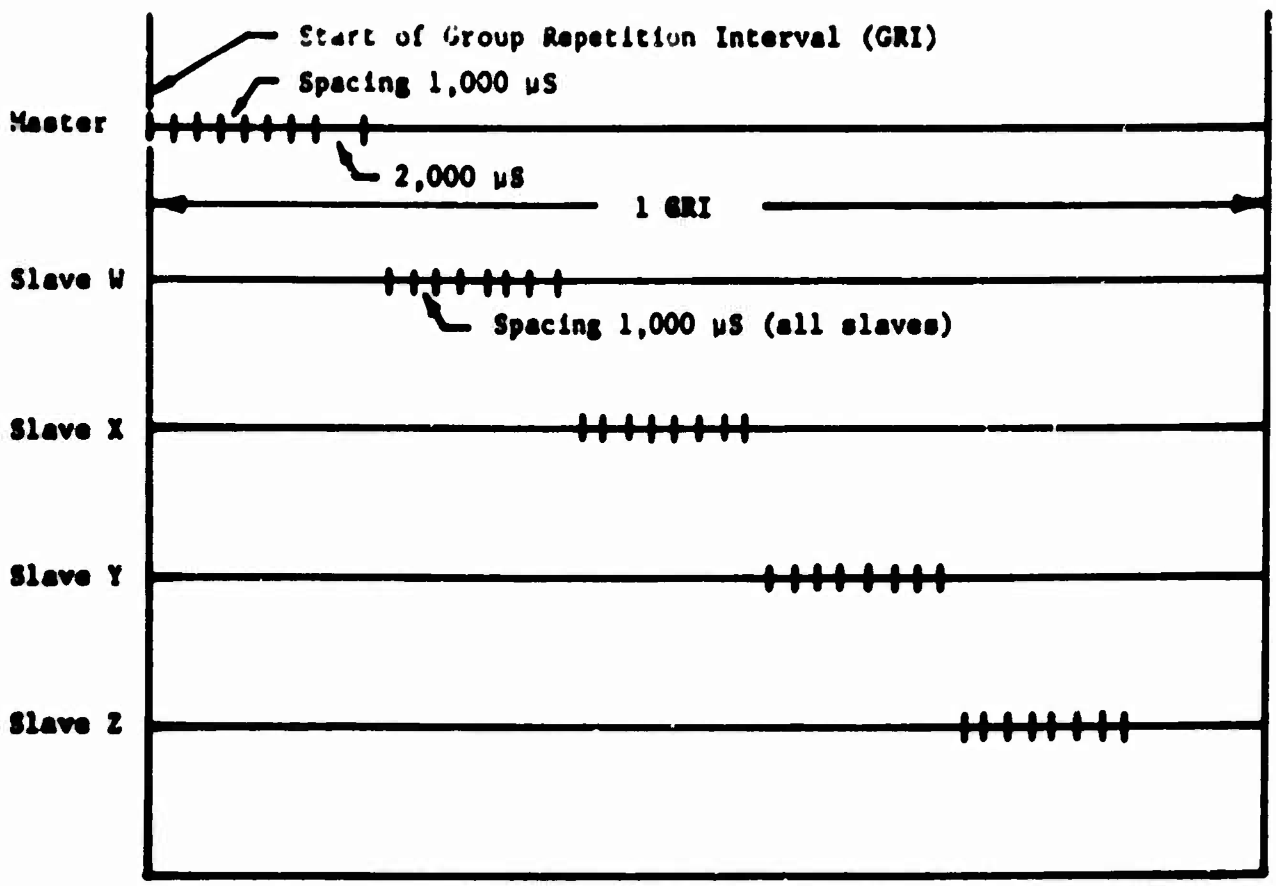
The master station blinks the ninth pulse to indicate that one or more of the chain legs are unusable for navigation. The ninth pulse is blinked in the Morse code for the character R (·–·) followed by one, two, three, or four dots (·) indicating unusability of the X, Y, Z, or W legs, respectively. The blink interval is twelve seconds. The slave stations blink their first two pulses; on for 0.25 seconds, off for 3.75 seconds (approximate) to indicate that their respective legs are unusable.

There are eight LORAN-C chains at present, all located in the Northern Hemisphere. Table I lists the pertinent data for all LORAN-C stations and reflects recent changes.

TIMING A LORAN-C CHAIN

LORAN-C chains are timed by synchronizing the transmissions of the master station to the U. S. Naval Observatory master clock. No special procedures are required at the slave stations, since they are already synchronised to the master station to fulfill the navigation requirement. Since most LORAN basic and specific rates are not submultiples of one second, there is only periodic coincidence between the LORAN pulse groups and a Universal Time Second (UTS, a second on the Universal Time Scale). For example, coincidence occurs every 3 seconds for rate SHO but only once every 999 seconds for rate SS1. Table II illustrates the basic and specific LORAN rates, and the period between coincidences for the rates. Because of the typically long baselines between stations, LORAN rates L and H are not used in the LORAN-C system. To provide knowledge of specific coincidences for the chains

PULSE GROUP FORMAT



PHASE CODE

	1st GRI	Alternate GRI
Master	+ + - - + - + -	+ + + + + - - +
Slave	+ - - + + + + +	+ - + - + + - -

Figure 2. LORAN C Pulse Group and Phase Code formats.

TABLE I. LORAN C STATION INFORMATION

CHAIN	RATE	STATIONS	EMISSION DELAY(μS)	POWER(kW)
U. S. EAST COAST	SS7	M Carolina Beach, N.C.		1,000
		W Jupiter, Fla.	13,695.48	400
		X Cape Race, Newfoundland	36,389.56	2,500
		Y Nantucket Is., Mass.	52,541.27	400
		Z Dana, Ind.	68,560.68	400
MEDITERRANEAN	SL1	M Simeri Crichi, Italy		300
		Y Targabarun, Turkey	32,273.28	300
		Z Estartit, Spain	50,999.68	300
NORWEGIAN SEA	SL3	M Ejde, Faroe Is.		400
		W Sylt, Germany	30,065.69	400
		X Bo, Norway	15,048.16	300
		Y Sandur, Iceland	48,944.47	1,500
		Z Jan Mayen, Norway	63,216.20	300
NORTH ATLANTIC	SL7	M Angissoq, Greenland		500
		W Sandur, Iceland	15,068.10	1,500
		X Ejde, Faroe Is.	27,803.80	400
		Z Cape Race, Newfoundland	48,212.80	2,500
NORTH PACIFIC	SH7	M St. Paul, Pribiloff Is.		400
		X Attu, Alaska	14,875.30	400
		Y Port Clarence, Alaska	31,069.07	1,800
		Z Sitkinak, Alaska	45,284.39	400
CENTRAL PACIFIC	S1	M Johnston Is.		400
		X Upolo Pt., Hawaii	15,972.44	400
		Y Kure, Midway Islands	34,253.02	400
NORTHWEST PACIFIC	SS3	M Iwo Jima, Bonin Islands		3,000
		W Marcus Island	15,283.94	3,000
		X Hokkaido, Japan	36,684.70	400
		Y Gesashi, Okinawa	59,463.34	400
		Z Yap, Caroline Islands	80,746.78	3,000
SOUTHEAST ASIA	SH3	M Sattahip, Thailand		400
		X Lampang, Thailand	13,182.87	400
		Y Con Son, South Vietnam	29,522.12	400
		Z Tan My, South Vietnam	43,807.30	400

TABLE II. BASIC AND SPECIFIC RATE AND COINCIDENCE INFORMATION.

BASIC AND SPECIFIC RATES: (pulse group repetition interval in microseconds)

Specific \ Basic	S	SH	SL	SS
0	50,000	60,000	80,000	100,000
1	49,900	59,900	79,900	99,900
2	49,800	59,800	79,800	99,800
3	49,700	59,700	79,700	99,700
4	49,600	59,600	79,600	99,600
5	49,500	59,500	79,500	99,500
6	49,400	59,400	79,400	99,400
7	49,300	59,300	79,300	99,300

PERIOD OF TIME BETWEEN UTS AND LORAN RATE COINCIDENCES: (in seconds)

Specific \ Basic	S	SH	SL	SS
0	1	3	2	1
1	499	599	799	999
2	249	299	399	499
3	497	597	797	997
4	31	149	199	249
5	99	119	159	199
6	247	297	397	497
7	493	593	793	993

in operation, null ephemeris table has been devised by the U S Naval Observatory (USNO). As an initial arbitrary epoch, all LORAN-C master stations are assumed to have transmitted their first pulse at $00^h\ 00^s$, 1 January 1958. The periodic coincidences are thus computed from this epoch and are tabulated in null ephemeris tables, covering a full year, which are published by the USNO in Time Service Announcement, Series 9.

When a master station is synchronized to UTC, special equipment is installed in order to ensure the PTTI reliability. This equipment includes multiple cesium standards, redundant rate generation and time-of-day devices, and sufficient battery power to withstand extended power failures. Only a catastrophic failure would prevent the station from knowing its correct transmission time. Even in that event, the slave stations or system monitor could direct the repositioning of the master transmissions. The special equipment also allows the master station to transmit an additional pulse, once per second (1 pps), which a user within range may utilize to recover or maintain time. This 1 pps transmission is inhibited during the time that it is coincident with the master's normal pulse group. User techniques will be addressed later in this paper.

The transmissions from timed LORAN-C chains are monitored by special Time Monitor Stations within the prime coverage area. The readings taken by these stations are forwarded to the USNO, correlated, and then published by the USNO in Daily Relative Phase Values, Series 4, which is available upon request.

COVERAGE

It is always difficult to exactly define limits of coverage for electromagnetic emissions, since many variables are involved (e.g., receiver sensitivity, atmospheric noise condition, propagation conditions,

conductivity, local noise and interference, etc.). Figure 3 illustrates the approximate groundwave coverage which is presently available from the four LORAN-C chains which have been permanently synchronized to the USNO master clock. These chains are: the U. S. East Coast, the Norwegian Sea, the Northwest Pacific, and the Central Pacific. Permanent synchronization is synonomous with having the special equipment installed at the master station. One additional chain, the Mediterranean, has been synchronized since July 1969 on a temporary basis in support of NASA's APOLLO missions. Another chain, the North Atlantic, is synchronized "de facto" since it operates in conjunction with time chains on either side of it. The daily values for these two latter chains are published by the USNO in addition to those for the permanently synchronized chains. Thus, the existing groundwave coverage for PTTI is considerably extended, if these two chains are included. Figure 4 illustrates the groundwave coverage which will be available when the remaining chains are timed. These two chains, the Southeast Asia and the North Pacific, are presently useful for relative PTTI on an intrachain basis since the operating frequency is on the UTC scale.

USER INSTRUMENTATION AND TECHNIQUES

Shapiro[3,4] has covered instrumentation methods in considerable detail and no effort will be made to duplicate that work. Instead, simple block diagrams and descriptions will be used to illustrate the types of instrumentation and techniques which may be used to recover PTTI from the received LORAN-C transmissions. Kramer[5] has all ready furnished details of receiver design and construction.

Previously, it was noted that an additional pulse, transmitted once per second, was available from timed master stations for those users within groundwave range. To utilize this pulse, an equipment configuration similar to that shown in Figure 5 is suggested. The band


EXISTING LORAN-C
TIMING

E

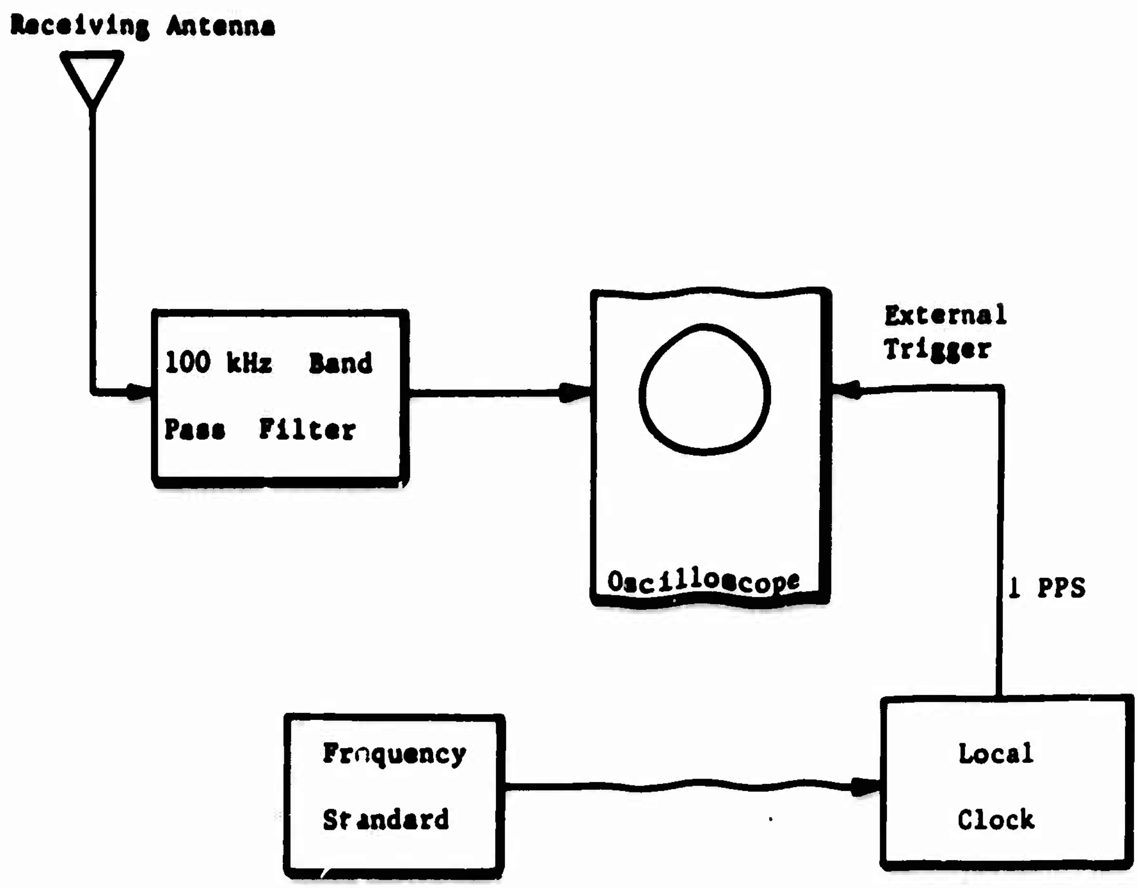


Figure 5. Instrumentation for utilization of the 1 PPS transmission from timed master stations.

pass filter is used to improve the signal-to-noise ratio and some notch filtering may be incorporated to eliminate interferring signals. The output of the band pass filter is applied to the vertical input amplifier of an oscilloscope which is externally triggered by the user's clock at a 1 pps rate. Thus, the received pulse will appear stationary on the oscilloscope screen and the delay between the start of the sweep and the start of the received pulse may be observed and measured. The availability of a calibrated delayed trigger will greatly facilitate this measurement. The observed delay is the sum of the propagation delay between the master station and the user's location (must be calculated by the user), any receiving system delays (normally furnished by the manufacturer), the published correction for the LORAN-C chain, and the user's clock error. Since the first three factors will be known, the user's clock error may be readily determined. One drawback to this technique is that identification of the start of the pulse is usually difficult unless the user is very close to the master station, since the signal-to-noise ratio is the poorest at the point of intended identification. However, the use of photographic or other integration methods will improve the identification process by effectively increasing the signal-to-noise ratio. The user costs for this type system can be very low. The cost of in-house fabrication of the antenna system and band pass filter would certainly not exceed \$150. Commercial versions of equipment to implement this technique are available for approximately \$700. This, of course, assumes that the user already has a frequency standard, clock, and oscilloscope. The precision obtained using the 1 pps transmission is clearly a function of the signal-to-noise ratio and the user's ability to determine delays accurately. Under ideal conditions submicrosecond precision is possible, although typical conditions would probably yield results in the 10-μsec regions.

The ultimate precision achievable is obtained by utilizing all of the pulses within the pulse groups transmitted from a single station. This provides the maximum information rate and the maximum signal-to-noise ratio for a given user location and equipment configuration. The equipment required is illustrated in Figure 6. The receiver contains not only signal processing circuits but also a phase-locked loop and digital circuitry to provide output triggers which are synchronized to the received LORAN-C carrier phase. The local frequency standard and clock are then used as inputs to a LORAN rate generator which is synchronized to the LORAN-C ephemeris table. The outputs of the LORAN rate generator and receiver are then used to start and stop (respectively) a time interval counter. At this point, depending on exact equipment configurations, the user has a choice of information (a counter reading update) at the rate of once every Group Repetition Interval (GRI), once every second, or once every Time Of Coincidence (TOC). The precision remains the same for all cases the differences lie in the digital circuitry involved. The counter reading again represents the sum of the propagation and emission delays between the LORAN-C station and the user's location, any receiving systems delays, the published correction for the LORAN-C chain, and the user's clock must initially be correct to within plus or minus one-half of the LORAN repetition interval in order to eliminate any ambiguity. User costs for this type PTTI recovery range from $7,000 to $10,000, assuming commercial procurement.

FREQUENCY CONTROL

One of the fringe benefits of phase-locking a local frequency standard to the received LORAN-C groundwave carrier phase is that the local standard does not have to exhibit good long-term stability on its own. Indeed, one may use a good quality crystal oscillator and take advantage

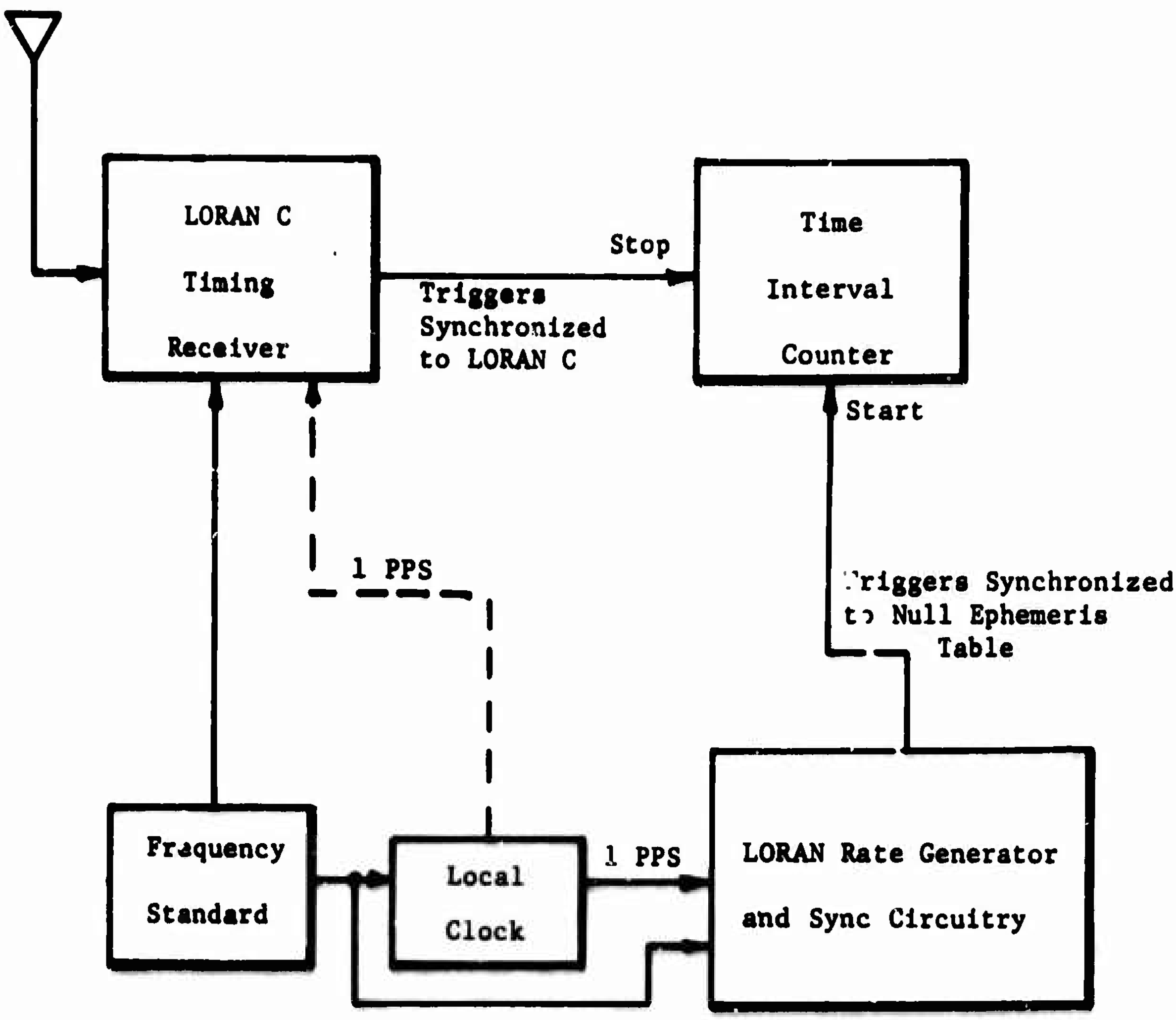


Figure 6. Instrumentation for utilization of the pulses within the LORAN C pulse groups.

of the excellent short-term stability while enjoying the excellent long-term stability of the cesium standard installed hundreds of miles away. This is possible since the groundwave at 100 KHz exhibits negligible diurnal shift. Stone[6] has demonstrated the success of this technique. In-house schemes may be employed at costs of less than $100, while commercial equipment is available in the range of $500 to $1,000, depending on optional accessories desired. Since the frequency of the LORAN-C chain is traceable to either the U. S. Naval Observatory or the National Bureau of Standards, the local standard output may be used to calibrate other equipment. It should not be necessary to point out that it may also be used to drive a precision clock.

The frequency of the radiated carrier at LORAN-C master stations is nominally maintained within $\pm 2 \times 10^{-12}$ with respect to UTC. It is typically within $\pm 1 \times 10^{-12}$, and on several occasions chains have been within 1×10^{-13} for a period of months. Although the slave stations operate in what is termed the "free running mode" (i.e., active phase-locked synchronization to the master received phase is not maintained and corrections necessary to maintain the required navigation synchronization are inserted as incremental phase steps), the frequency of the slave cesium standards is rigidly maintained within $\pm 5 \times 10^{-13}$ with respect to the master station standard in order to minimize the necessary phase corrections. Consequently, a user who phase-locks his local standard to the received carrier phase from a slave station is in fact (for periods in excess of one day) phase-locked to the master carrier as well; and the frequency of the received slave carrier may be considered identical to that of the master station frequency standard.

PRECISION

Pakos[7] has given a great deal of attention to the error budgets involved in LORAN-C timing from the user's standpoint. That work will not be repeated here, but can be summarized quite readily. Pakos' one sigma error estimates of the different error sources are:

- System error, $\sigma_{SE} = 3.0\ \mu$sec
- User prediction error, $\sigma_{PE} = 0.1\ \mu$sec
- Groundwave propagation anomoly (over land), $\sigma_{PA} = 0.2\ \mu$sec
- Slave synchronization error, $\sigma_{SS} = 0.05\ \mu$sec
- UTC tolerance,* $\sigma_{UT} = 2.0\ \mu$sec
- User measurement error, $\sigma_{ME} = 0.1\ \mu$sec

Using these values, one can calculate that two users who wish to synchronize to each other (but not to UTC) and who are within groundwave range of the same master station may expect an rms error of 0.35 μsec. On the other hand, a user who wishes to synchronize a clock to UTC using a slave station could expect an rms error of 3.6 μsec. However, if the user was willing to wait a day to remove the UTC error and had been visited once by a portable clock (to remove prediction and system errors), he could expect the rms error to be reduced to 0.27 μsec. The best use under the error estimates given by Pakos would be made by one who used a master station for synchronization, waited a day to remove the UTC error, had been visited once by a portable clock, and whose propagation path from the master station was over seawater. In this case the rms error would be the measurement error, 0.1 μsec. The advantages of a single portable clock visit to the user's site to "calibrate" the receiving system are quite obvious.

---

*This is really an uncertainty figure and does not relate to the operational UTC tolerance held by the chains.

Analysis of the data contained in the USNO's Daily Relative Phase Values, Series 4, is quite revealing. The data was processed in the following manner: First, the daily values were plotted with intentional (announced) time steps removed. The resultant curves were then partitioned to segregate periods of operation free of frequency or other adjustments. Then a linear regression was performed on the data to determine frequency offset and the degree of correlation. Next the slope and mean value were removed and the standard deviation was calculated. The results are as indicated in Table III. Further analysis of the results reveal an expected value of 0.35 μsec for 2,832 samples (days). This effectively represents approximately eight years of data. On the basis of these results Pakos' one sigma error estimate for the UTC tolerance would appear to be excessive. If we stipulate that the system error can be removed by calibration (work has already begun), then one of the two major error sources is removed and the other is reduced to a value commensurate with the remaining factors in the error budget. Returning for a moment to the case of the user who wishes to synchronize to UTC using a slave station (rms error previously reported as 3.6 μsec), recalculating the rms error using the new estimate for σ_{UT}(0.35) and assuming σ_{SE} equals zero, we find that the rms error is now calculated to be 0.43 μsec. Recall that this user has not been visited by a portable clock and does not know the chain correction for the day of measurement. This recalculated rms error agrees well with the author's experience in field measurements.

SKYWAVE USE

Thus far, only groundwave coverage and precision have been mentioned, although LORAN-C skywaves offer an excellent modem for PTTI dissemination if slightly degraded accuracy is acceptable. An offsetting advantage lies in the fact that time recovery from LORAN-C

TABLE III. RESULTS OF ANALYSIS OF PUBLISHED LORAN C DAILY RELATIVE PHASE VALUES

CHAIN	PERIOD	NO. OF DAYS	σ(μS)	R*
U. S. EAST COAST	FEB 1, 1968 - JAN 15, 1969	349	0.89	.90
	JAN 16 - MAR 30, 1969	74	0.18	†
	MAR 31 - AUG 25, 1969	148	0.38	.96
	AUG 26 - NOV 1, 1969	67	0.19	.98
	NOV 2 - DEC 12, 1969	42	0.11	.99
	DEC 13, 1969 - FEB 12, 1970	62	0.28	†
	FEB 13 - JUL 7, 1970	145	0.40	.98
	AUG 8 - SEP 17, 1970	41	0.08	1.00
	SEP 18 - NOV 18, 1970	62	0.12	†
NORTH ATLANTIC	JAN 1 - JUL 2, 1970	181	0.40	.96
	JUL 3 - NOV 18, 1970	140	0.30	†
NORWEGIAN SEA	OCT 15, 1968 - MAR 30, 1969	168	0.49	.94
	MAR 31 - NOV 14, 1970	279	0.43	.98
	NOV 15, 1969 - JAN 20, 1970	67	0.29	.97
	JAN 21 - APR 12, 1970	82	0.27	.99
	APR 13 - JUL 30, 1970	109	0.35	.96
	JUL 31 - NOV 18, 1970	111	0.28	.99
MEDITERRANEAN SEA	NOV 1, 1969 - FEB 12, 1970	104	0.40	†
	FEB 12 - JUN 16, 1970	124	0.33	.92
	JUN 24 - OCT 3, 1970	102	0.39	.96
	OCT 4 - NOV 19, 1970	47	0.20	.90
CENTRAL PACIFIC	FEB 11 - MAR 31, 1970	49	0.17	†
	APR 13 - MAY 26, 1970	44	0.30	.94
	MAY 27 - JUL 19, 1970	54	0.15	.87
	JUL 20 - NOV 17, 1970	121	0.45	.97
NORTHWEST PACIFIC	(NOT ANALYZED)			

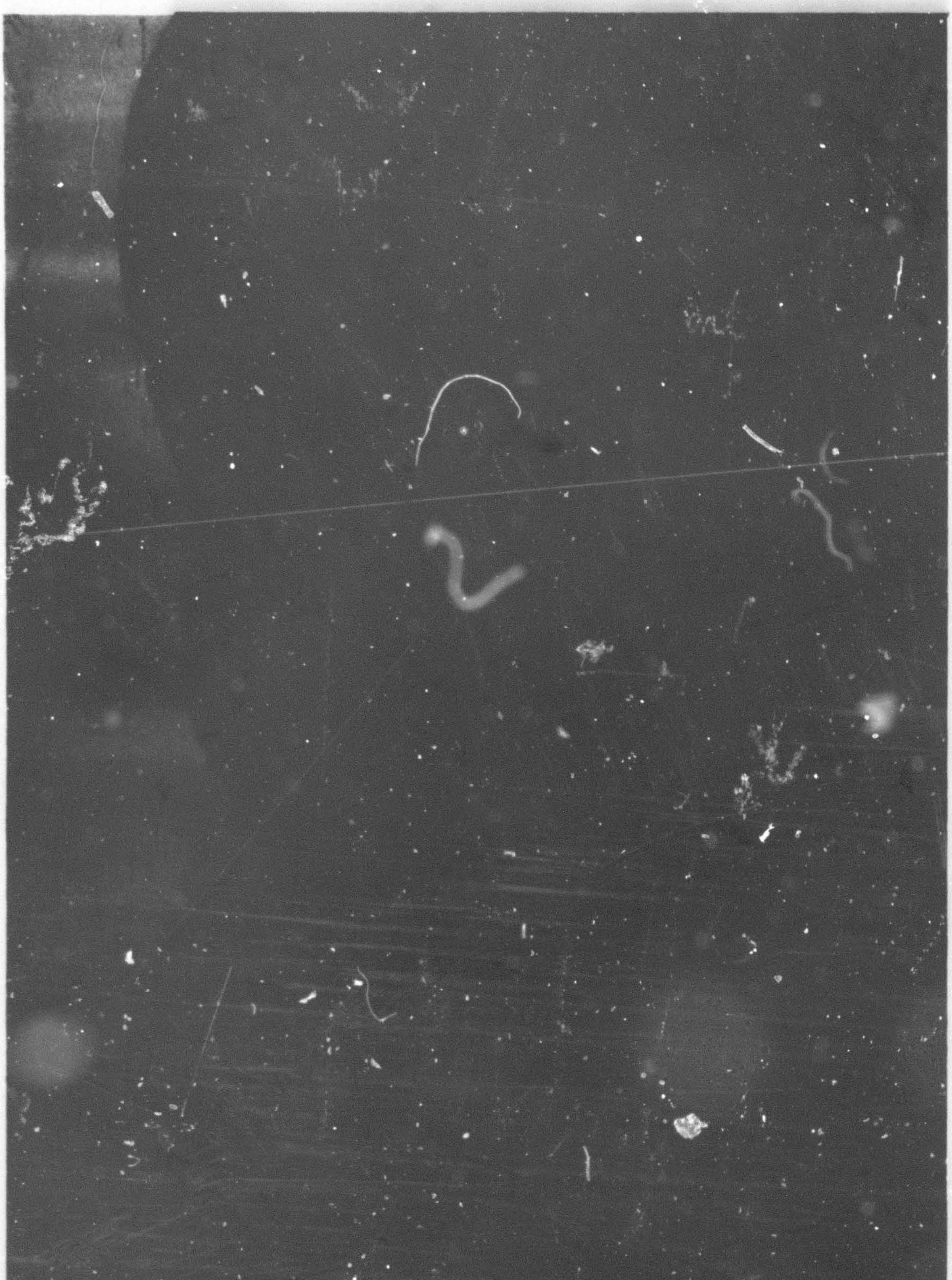
*R is the linear regression correlation coefficient. Computer program failure to yield the correct value due to the very small slope involved is signified by †. An R = 1.00 indicates a perfect fit of the data points to the linear expression.

skywaves is readily achievable at thousands of miles using both one hop and multi-hop propagation modes. In many instances these measurements may be carried out with visual receiving equipment at very low cost.[8] A single visit to the user's site with a portable clock to calibrate propagation delay can reduce the error budget to within an order of magnitude equal to that available with groundwaves. Where poor signal-to-noise ratio and interferring signals are a problem, special equipment may be employed to recover the LORAN-C pulse.[9] The maximum precision is achieved when a single propagation path is used and the observations are made at the same time each day. Figure 7 illustrates the potential skywave coverage, which is effectively the area north of 40° south latitude.

The National Aeronautics and Space Administration (NASA) is currently conducting a year long study of LORAN-C skywave stability, after some initial brief tests which resulted in synchronization capabilities on the order of several microseconds. More data and investigation are required to fully understand and take advantage of the ultimate potential of LORAN-C skywaves for PTTI dissemination. Nevertheless, skywaves may be utilized without correction practically worldwide, with accuracy in the 50-μsec region.

PRESENT OPERATION

Timed LORAN-C chains are currently held to a $\pm$ 15 μsec tolerance with respect to UTC through a coordinated arrangement between the U.S. Coast Guard and the U. S. Naval Observatory. Two types of corrections are employed to maintain this tolerance. They are infrequent step adjustments in the time of transmission of the chain, usually on the order of 10 μsecs or less and always announced in advance; and infrequent C-field adjustments to the operating cesium beam frequency standard at



the master station, usually on the order of 1×10^{-12}. Although the tolerance is ± 15 μsecs, the daily relative phase values are published to 0.1 μsec. If the requirement were presented, the tolerance could be reduced to $\pm$ 5 μsecs almost immediately.

FUTURE OPERATION

Recently the Department of Defense approved a proposal to implement UTC synchronization on all of the existing LORAN-C chains. At the time this program is implemented, it should be entirely possible to further reduce the tolerance to $\pm$ 1 μsec, although some investigative work is required. Improvements in the time monitor and master station equipment and measurement techniques should provide substantial reductions in the user's error budget. A burgeoning interest in LORAN-C timing should produce lower costs for commercial LORAN-C timing equipment. Studies of skywave stability should yield quantitative information to facilitate one hop and multi-hop propagation delay prediction and to produce a better model of the ionosphere.

LORAN-C PTTI USERS

It is worthy of mention to note the diverse interests and techniques which have or are utilizing LORAN-C PTTI; to wit, NASA's Manned Space Flight Network, intercontinental surveying, aerial mapping, long baseline interferometry, missile ranges, propagation studies, commercial peddlers of time, instrument calibration, communications, power companies for frequency control, and international bureaus and observatories for the maintenance and dissemination of the International Atomic Time Scale.

CONCLUSIONS

LORAN-C provides an excellent medium for the dissemination of PTTI on a continuous basis in both groundwave and skywave modes. User costs are not excessive and they vary, depending on the mode of propagation chosen and precision required. Expansion of the present system to all chains will enhance the coverage already available. At the same time, spectrum conservation and cost effectiveness are both achieved, since the system already exists to fulfill a separate (although related) requirement.

REFERENCES

[1] "The Loran-C System of Navigation," Jansky and Bailey, Inc., Washington, D.C., February 1962.

[2] Kelly, C.T., Jr., "Use of Loran In the Range-Range Mode," Navigation, Vol. 16, No. 4, Winter 1969-70.

[3] Shapiro, L.D., "Time Synchronization from Loran-C." IEEE Spectrum, August 1968.

[4] Shapiro, L.D. and Fisher, D.O., "Using Loran-C Transmissions for Long Baseline Synchronization," Radio Science, Vol. 5, No. 10, October 1970.

[5] Kramer, G., "LORAN-C Timing Receivers," Frequency Technology, August/September 1970.

[6] Stone, C.S., "A Frequency Control Experiment," Austron, Inc. Technical Note 168-2.

[7] Pakos, P.E., "Use of the Loran-C System for Time and Frequency Dissemination," Frequency Technology, July 1969.

[8] Shapiro, L.D., "Loran-C Sky-Wave Delay Measurements," IEEE Transactions on Instrumentation and Measurement, Vol. IM-17, No. 4, December 1968.

[9] Stone, C.S., "Loran-C Skywave Timing Experiment," Austron, Inc. Technical Note 168-1.

SATELLITE COMMUNICATIONS SYSTEM

by J. A. Murray*

INTRODUCTION

The responsibility of the Naval Observatory to maintain precise time coordination on a worldwide basis requires frequent comparisons of distant time standards with the Observatory reference clock. Perhaps the best available means of making these comparisons has been to transport accurately calibrated atomic clocks from the Observatory to the distant locations and to make direct on-site measurements. This method however accurate, is also expensive.

TIME TRANSFER VIA SATELLITE

The use of communications satellites to perform the long-distance comparisons (or time transfers) has been investigated and proved feasible. The Defense Satellite Communications System (DSCS) contains the potential for making the accurate Observatory reference economically available to many vital areas of the world.

Under sponsorship of the Naval Electronics Systems Command and with the cooperation of the Observatory and Defense Communications Agency (DCA), the Laboratory has produced techniques for using certain DSCS links in a noninterfering manner, and successful time transfers have been made on an experimental basis. Use of DCA facilities on an operational basis is planned for the near future.

---

*Radio Time and Frequency Section, Naval Research Laboratory, Washington, D. C. (202) 767-3309.

The planned time-distribution system would place Observatory-controlled, precise reference clocks at satellite communications (SATCOM) terminals in key areas (see Figure 1). Further distribution will be accomplished by short-distance clock transports or any of a number of short-range techniques to be described in other presentations.

A clock maintained at a SATCOM location near the Observatory will be disciplined by the Observatory standard through comparisons over a direct microwave link or by carrying clocks regularly from the Observatory to the terminal. The clock maintained at the distant SATCOM facility will be updated periodically by comparisons through the DSCS satellite. Since the clocks at the two terminals are held to a nearly constant rate by atomic frequency standards, they need not be compared continuously, but time transfers may be made daily, weekly, or monthly, depending upon the stability of the clocks, the availability of the satellite link, and the required time accuracy.

Use of the satellite system, however, is not unidirectionally beneficial. The time-reference equipment may be used to considerable advantage by the SATCOM terminals in their synchronization procedures, as shown in Figure 2.

Basically, the time-transfer system is not required to insert signals or disturb the operation of station equipment if the terminals are equipped with AN/URC-55 communications modems. The synchronizing signals shown being injected into the modems (see Figure 2) are used only to aid in modem synchronization and are not required for the time transfer. All signals required by the time-transfer unit are available at test points on the modem.

The feature of the modem that makes it useful in time transfers is its high speed pseudo-random code stream. The transmitter section of each modem generates such a stream (see Figure 3), and a code generator

TIME REFERENCE SERVICE VIA SATELLITE

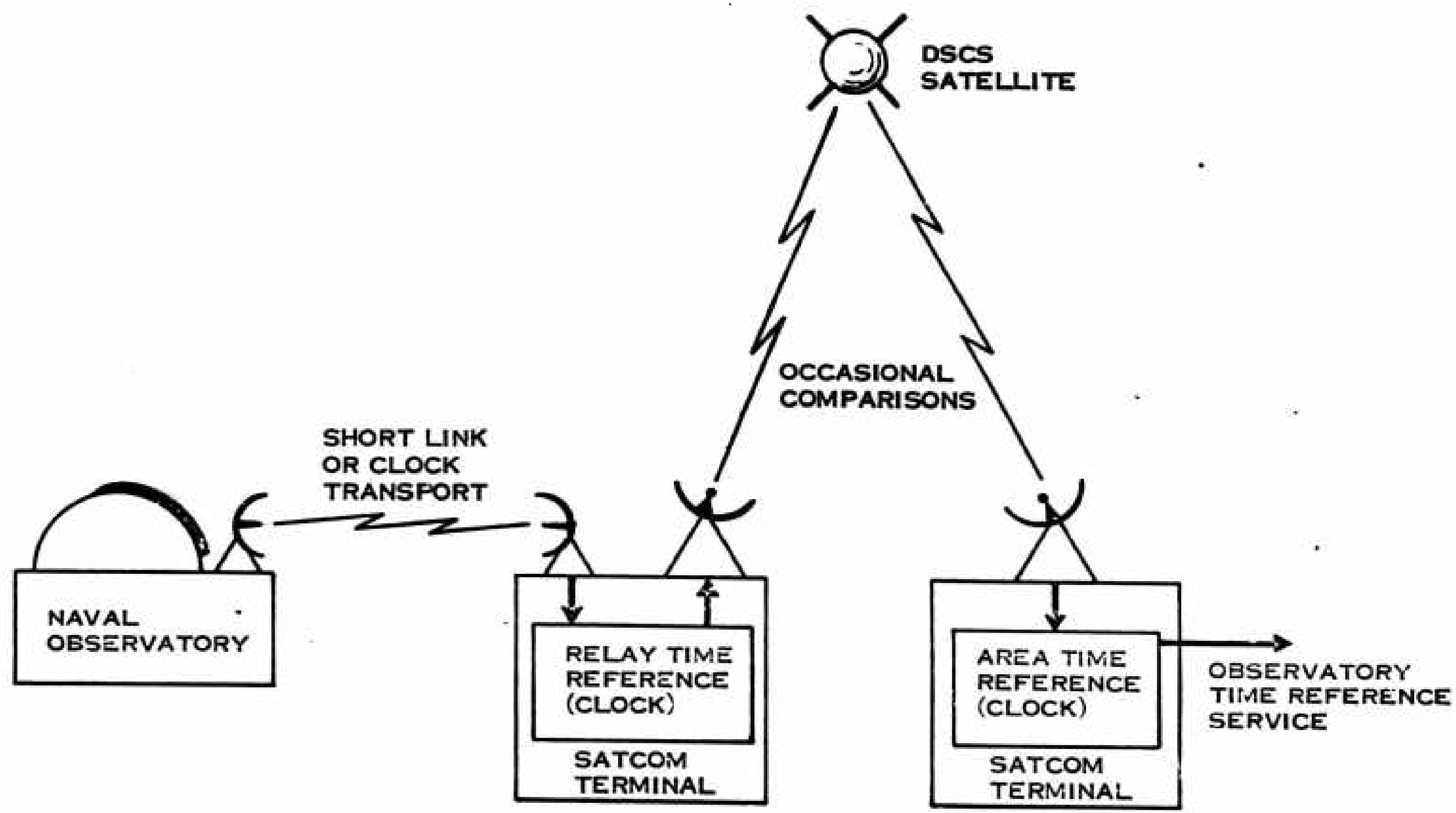


FIGURE 1

TIME TRANSFER BY COMMUNICATION SATELLITE

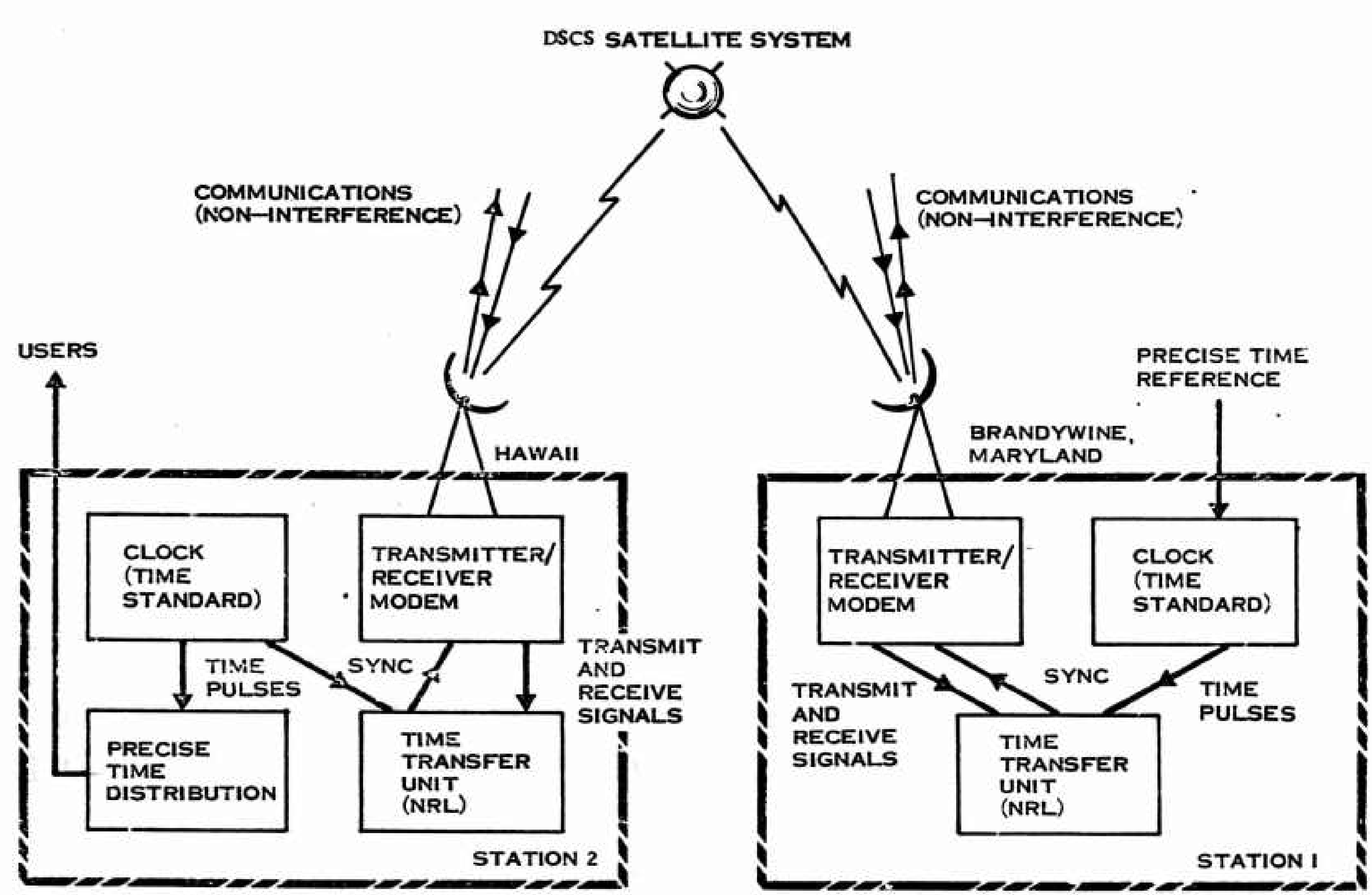


FIGURE 2

XMIT–RCV PN CODE

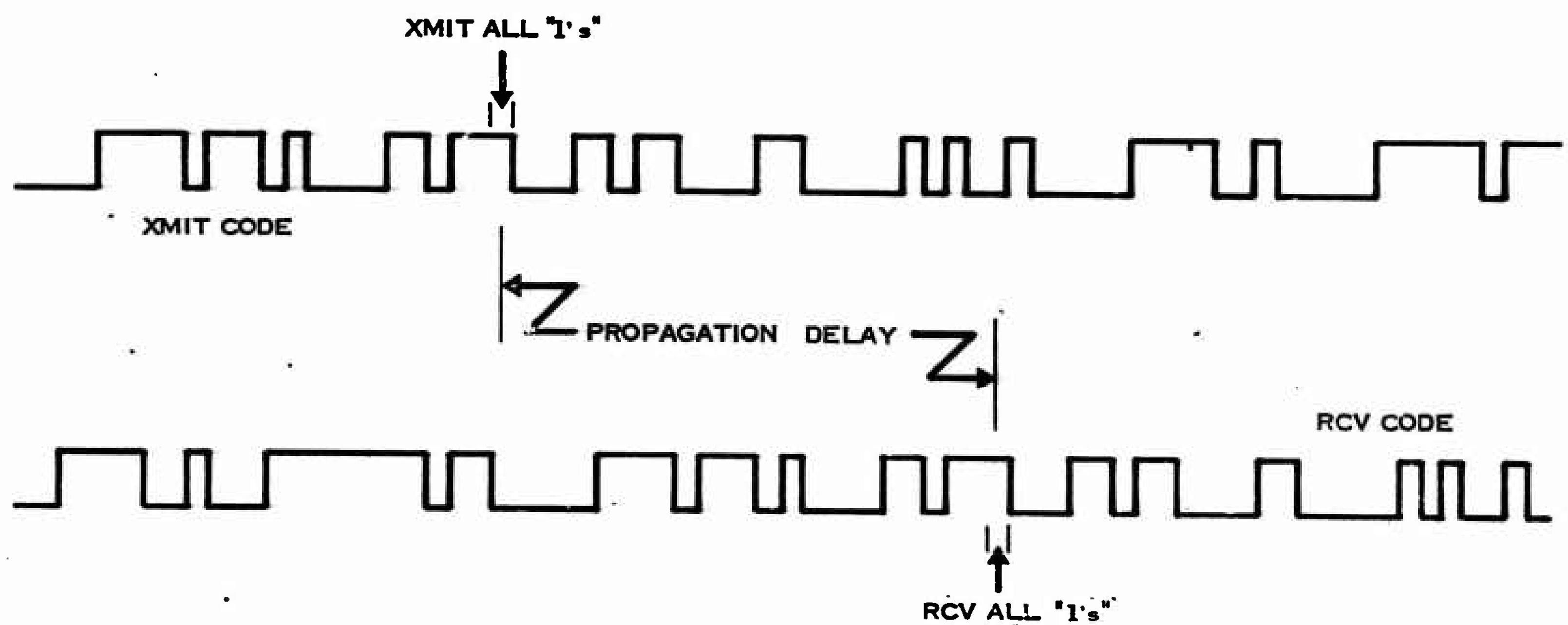


FIGURE 3

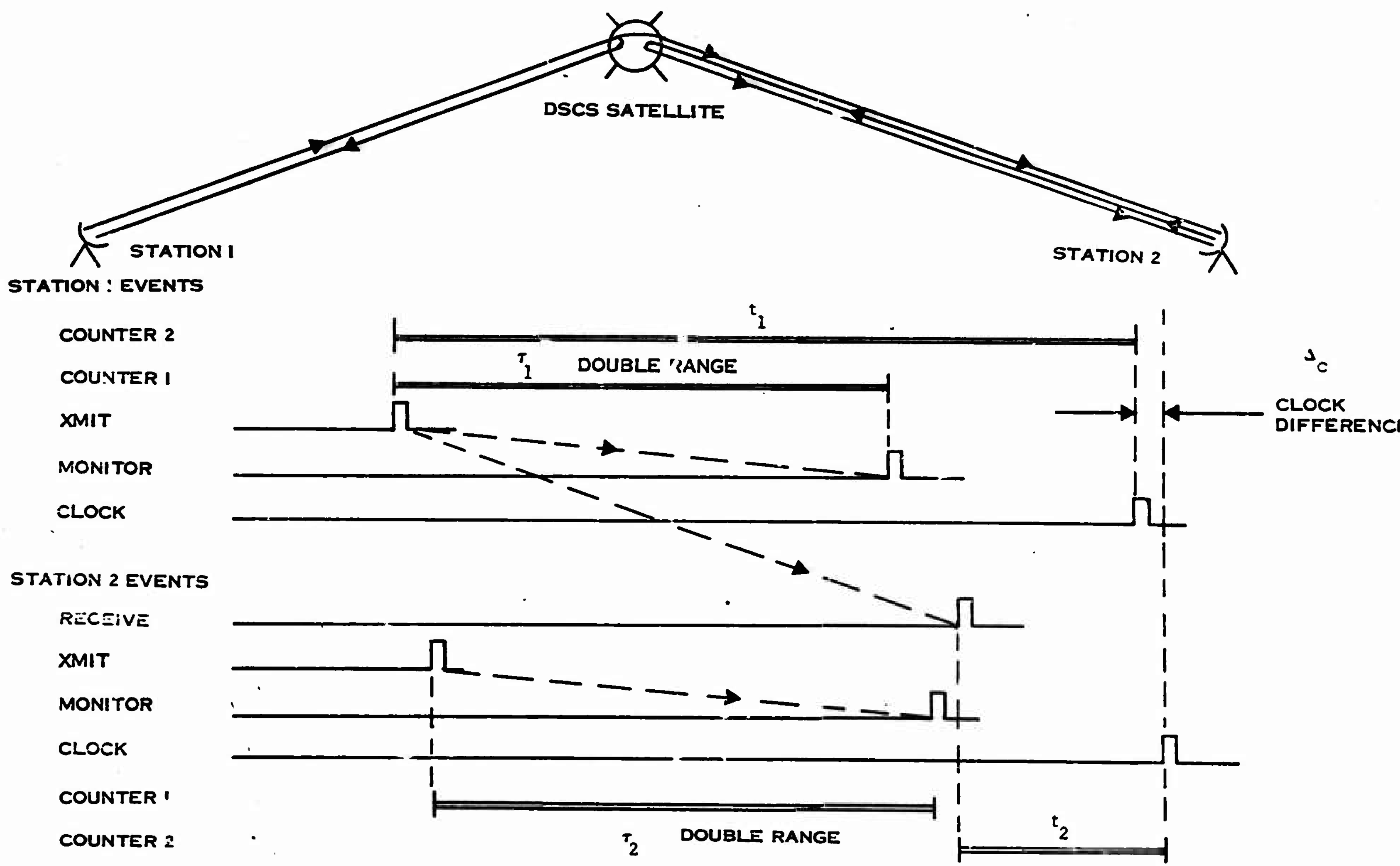
in the receiver section of the modem at the other station matches the stream as received. It is possible, then, to extract from each modem certain recognizable code generator states, or "ticks" (designated "all-one's" in the diagram), that can be treated as though they were very short pulses transmitted by one modem and received by the other. The tick at the receiver is delayed, of course, by the time it takes the transmitted signal to travel from the transmitter to the satellite and back down to the receiver. In addition to the transmit tick and receive tick, each modem provides a "monitor" tick that corresponds to the reception of its own transmit tick after a round trip to the satellite and back.

TIME-TRANSFER TECHNIQUES

Two methods of time transfer have been used. In the method shown in Figure 4, each station measures its round-trip distance to the satellite; at the same time, station 1 compares its transmit tick with its own clock to obtain the time interval t_1, and station 2 compares the corresponding receive tick with its own clock to obtain t_2. By using half the sum of the two double range measurements τ_1 and τ_2, the time of flight from station 1 to station 2 is determined and, in effect, added as a correction to the receive tick at station 2. The difference between the transmit reading at station 1 and the corrected receive reading at station 2 is the difference between the station 1 and station 2 clocks. After the two time-interval measurements, t_1 and τ_1 recorded at station 1 or the interval measurements t_2 and τ_2 recorded at station 2, are communicated to the opposite station, the clock difference may be determined and corrected.

In the second time-transfer method (see Figure 5), each station measures its own transmit tick with respect to its clock and also measures the tick received from the other station with respect to the same clock. If the sum of the measurements at one station is subtracted from

EXPERIMENTAL TIME TRANSFER TIMING DIAGRAM



$$\Delta_c = \frac{\tau_1}{2} + \frac{\tau_2}{2} + t_2 - t_1$$

FIGURE 4

TIME TRANSFER TIMING DIAGRAM

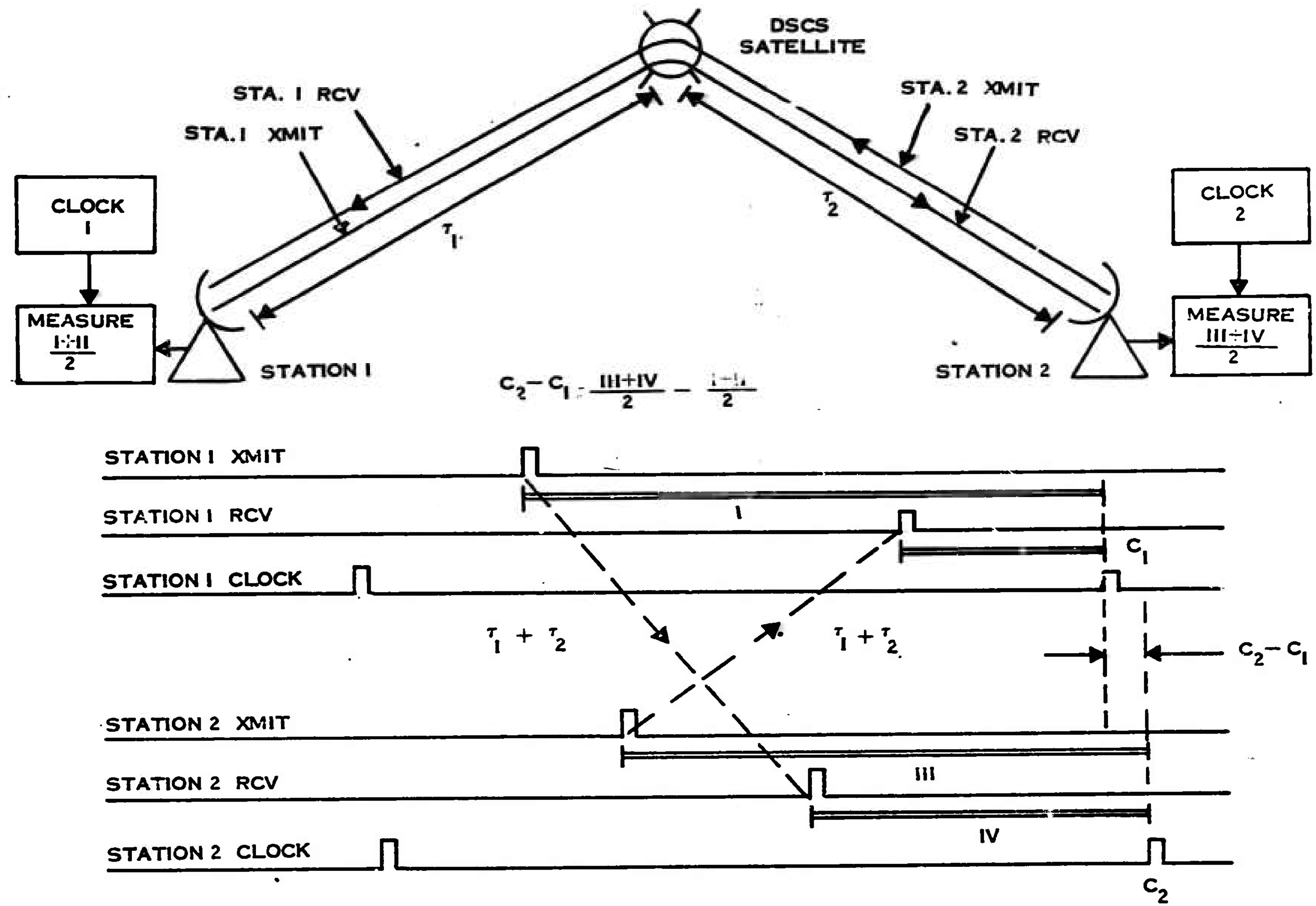


FIGURE 5

the sum of the measurements taken at the other station, the result is twice the difference between the two clocks. This method uses identical equipment and procedures at the two stations.

INTERFACE EQUIPMENT

A time-transfer unit (see Figure 6) has been designed as an interface to operate automatically in the latter method and yield a single reading at each station. The difference between clocks is simply the difference between the numbers produced at the two stations.

With either time-transfer method, however, it is necessary to transmit data from one station to the other in order to make the clock-difference determination. This is normally done through the order wire between stations.

The two methods are valid, in general, only if the transmitted ticks from both stations arrive at the satellite at nearly the same time. This is ensured if the modems of the two stations have made a tick start, an easily accomplished procedure when accurate local clocks are available. Although provisions have been made in the time-transfer unit for making tick starts with the accurate clocks of the time-transfer system, under some circumstances, a "reset" start of the modems might be made instead. In this case, the ticks of the two stations might pass through the satellite at widely separated times and the motion of the satellite between the two passages could produce an unacceptable error in the time transfer.

To compensate for this error, the range measurements may be interpolated in the first method. For the second method, an interpolation procedure has also been worked out. Although it is inconvenient to use the interpolation procedures, they apparently add little to the inaccuracies of the time transfer.

EXPERIMENTAL RESULTS

In February 1970, time-transfer tests were run between the SATCOM stations at Brandywine, Maryland, and Ft. Dix, New Jersey, to prove the feasibility of using the pseudo-random code stream. Further tests were run between Brandywine, and the SATCOM facility at Helemano, Hawaii. Figure 7 shows a quite consistent grouping of results for that test. (No explanation is offered for the single reading approximately 0.7 μsec away from the mean. It could have resulted from a misread counter.) Much of the spread (approximately 0.3 μsec) may be attributed to quantization error, since the least significant digit of each counter was 0.1 μsec. Somewhat better results were obtained on a smaller sample later during the same test period.

In a still later series of tests, a small sample of measurements yielded a standard deviation of less than 0.1 μsec. A group of measurements made by interpolation disagreed with the group made with synchronized modems by less than 0.1 μsec. During the same period, a time transfer made by transporting a clock to Hawaii and back to Maryland disagreed with the satellite time transfer by approximately 0.3 μsec. The clock transport, however, was not ideal because of a relatively large rate offset in the portable clock and some delay in making the comparison after its return to Maryland. In spite of these shortcomings, it appeared that the inaccuracy of the satellite time transfer was not greater than 0.5 μsec and possibly much smaller. Future tests are expected to yield a more accurate picture of its performance.

An improvement in measurement resolution is likely to improve overall repeatability, if not accuracy, because most of the observed spread in readings can be attributed to instrumentation uncertainty. After the least significant digits of the readout devices have been reduced to .01 μsec, it is planned to make more detailed assessments of the systems capabilities.

DSCS TIME TRANSFER EXPERIMENT
HELEMANO, HAWAII - BRANDYWINE, MARYLAND
(TEST A)

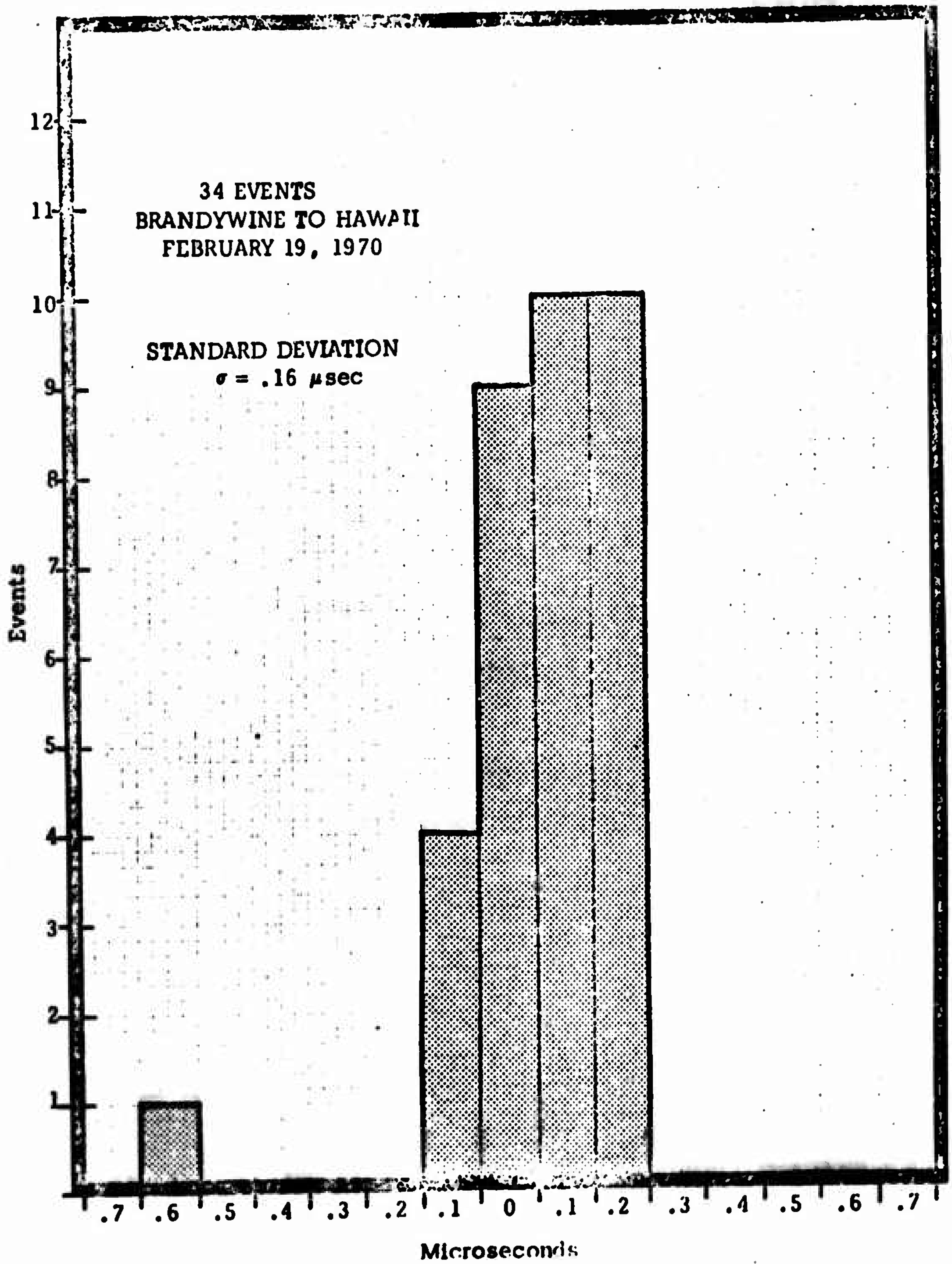


FIGURE 7

Differential time delays between transmitting and receiving terminal equipment produce small fixed time offsets. Since the individual contributions of the various station components are small and are complicated by frequency conversions, it may be difficult to analyze them individually. Instead, it will probably be necessary to make overall station comparisons to determine the absolute accuracy of the satellite time transfers. It is expected that the effects of the differential delays will prove to be less than 0.1 μsec.

TIME-TRANSFER MODEM

A modem intended specifically for time transfers at terminals not equipped with communications modems has been recently designed and constructed. This modem employs a pseudo-random code that operates at a 10-MHz bit rate and goes through its complete cycle in 819 μsecs as shown in Figure 8. Since the recognizable all-one's events recur once each 819 μsecs other information must be transmitted by the modem to identify which all-one's event is the intended time tick. As seen, the transmitter responds to an initiating pulse by reversing the phase of the code throughout the next code cycle. The all-one's event that terminates that cycle is the designated tick. At the receiver, the all-one's event that occurs at the end of the phase reversal is similarly recognized as the tick.

Time transfers are made by initiating time ticks at prearranged times, such as the beginning of each minute. The transmitted and received ticks produced by the time-transfer modem at each station are provided to the time-transfer unit, which performs the necessary time-interval measurements.

Because of the comparatively low relative velocity of DSCS satellites, it is not necessary to have the signals of both stations reach the satellite at precisely the same time. In fact, a 1-second difference in arrival time

SIGNAL TRANSMISSION BY TIME TRANSFER MODEM

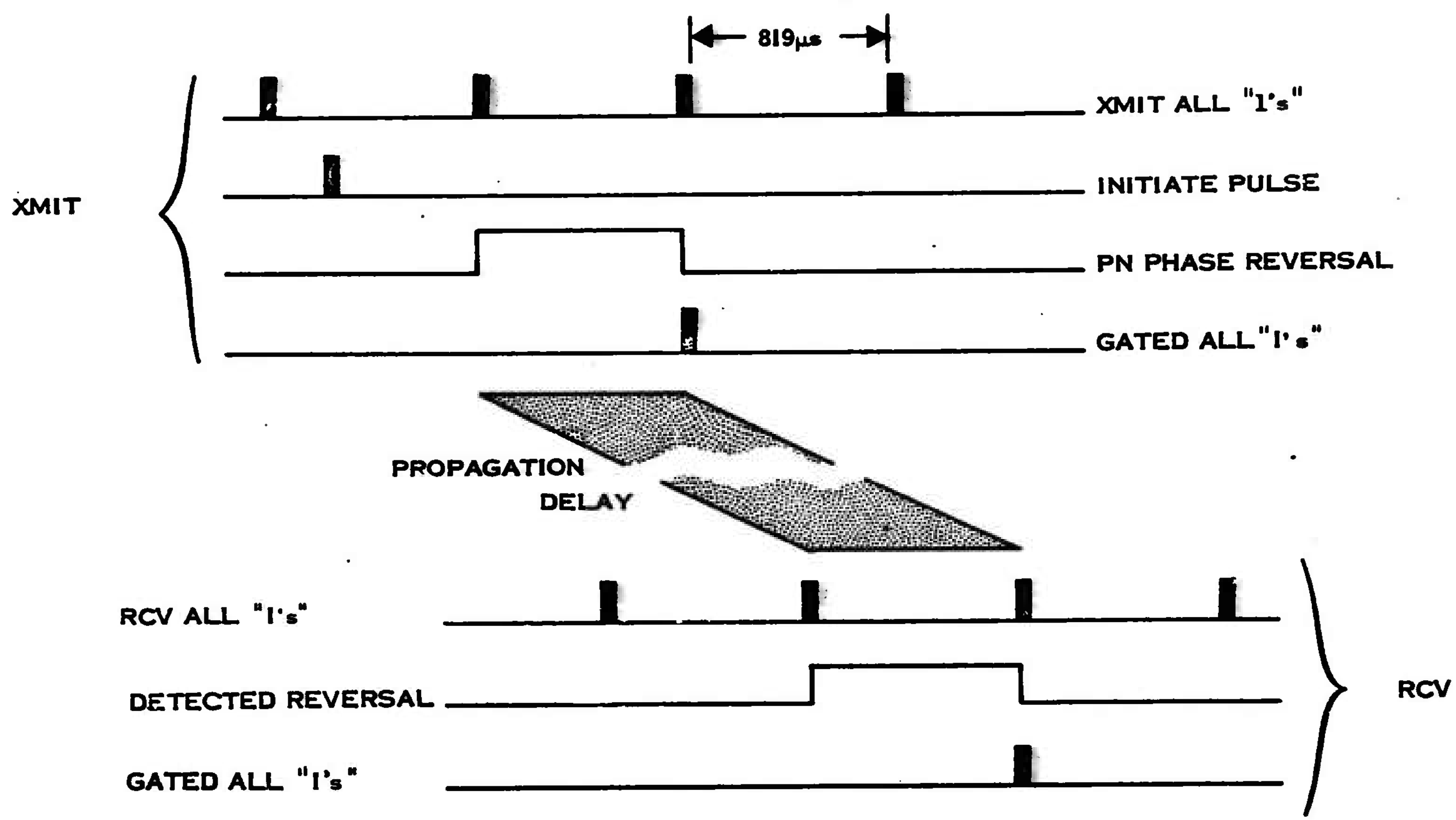


FIGURE 8

produces a time-transfer error in the order of only 0.1 μsec. Therefore, the only requirement for control of the transmissions is that they be launched within a fraction of a second of each other. When the time-transfer modem is used, this requirement is satisfied if the clocks at the two stations agree within a fraction of a second.

A very much simplified diagram of the time-transfer modem is shown in Figure 9. The lower section is the transmitter, which produces a pseudo-random modulated 70-MHz signal. The code stream polarity (hence the polarity of the output signal) is reversed for one code interval after the command pulse is received. The polarity inversion sequence circuit also produces the gated all-one's pulse that constitutes the transmit-time tick.

The receiver section shown in the upper portion of the diagram could receive the output of the transmitter and recover the time tick if the transmitter output were connected to the receiver input. However, in making a time transfer, the receiver should respond only to the transmission of the modem at the other station. This is ensured by transmitting a different code from each station. The receiver at station 1, for example, uses the station 2 transmitter code and, therefore, ignores the station 1 transmitter.

Range measurements may be made by using a common transmit and receive code at one station. The receiver then responds to the local transmitted signal after its round trip to the satellite. The time interval from the transmit tick to the receive tick then corresponds to the double-range propagation time.

In the receiver, the local conversion oscillator is bi-phase modulated with the same code that modulated the received signal. After the two codes have been aligned by a searching process, each phase inversion of the received signal is accompanied by a phase inversion of the local oscillator. The intermediate-frequency output of the modulator, therefore, is a constant-phase signal.

TIME TRANSFER MODEM TRANSMITTER AND RECEIVER

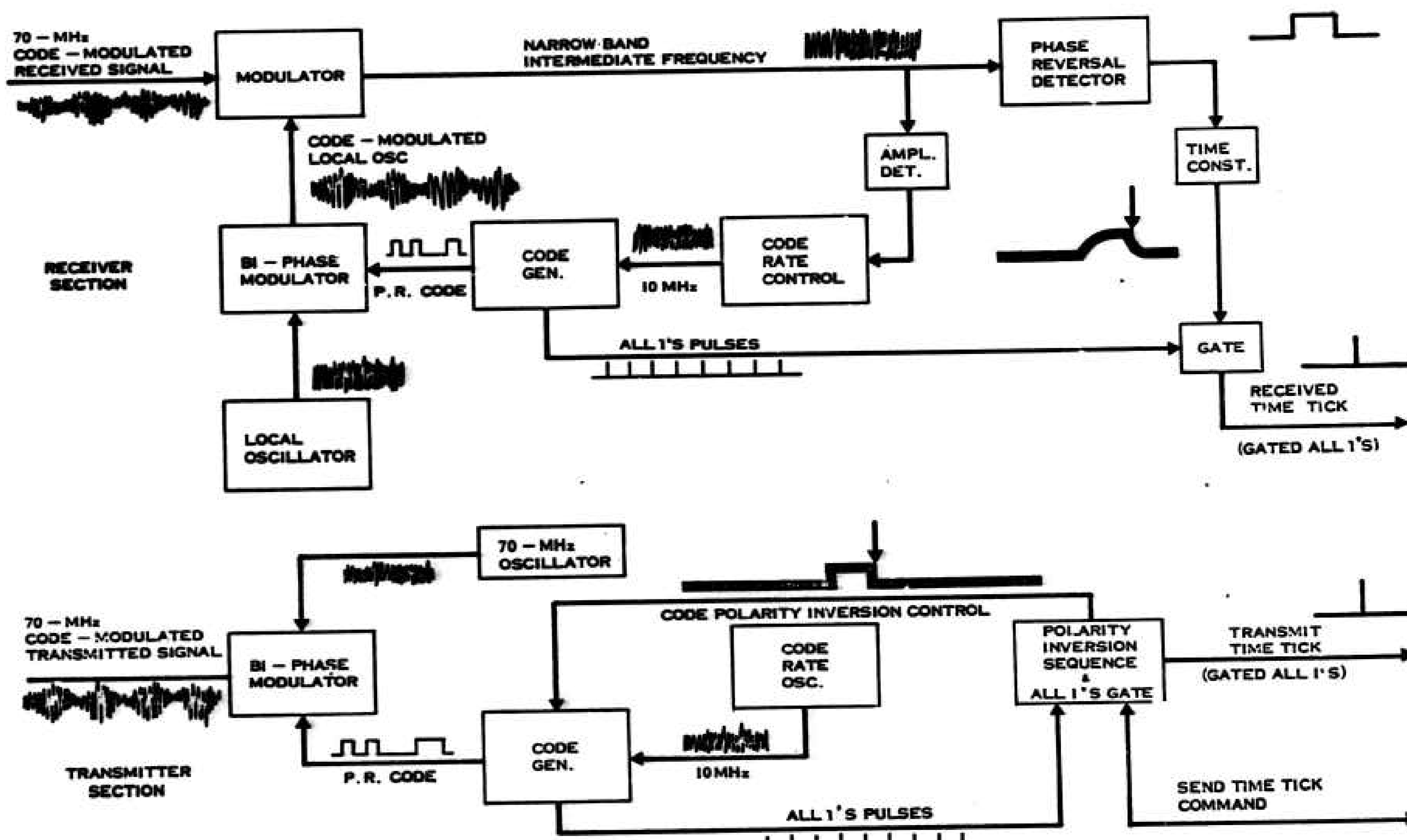


FIGURE 9

Since any misalignment of the code modulation of the two signals results in an amplitude change at the intermediate frequency, the rate of the receiver code generator is controlled to maintain peak intermediate-frequency amplitude.

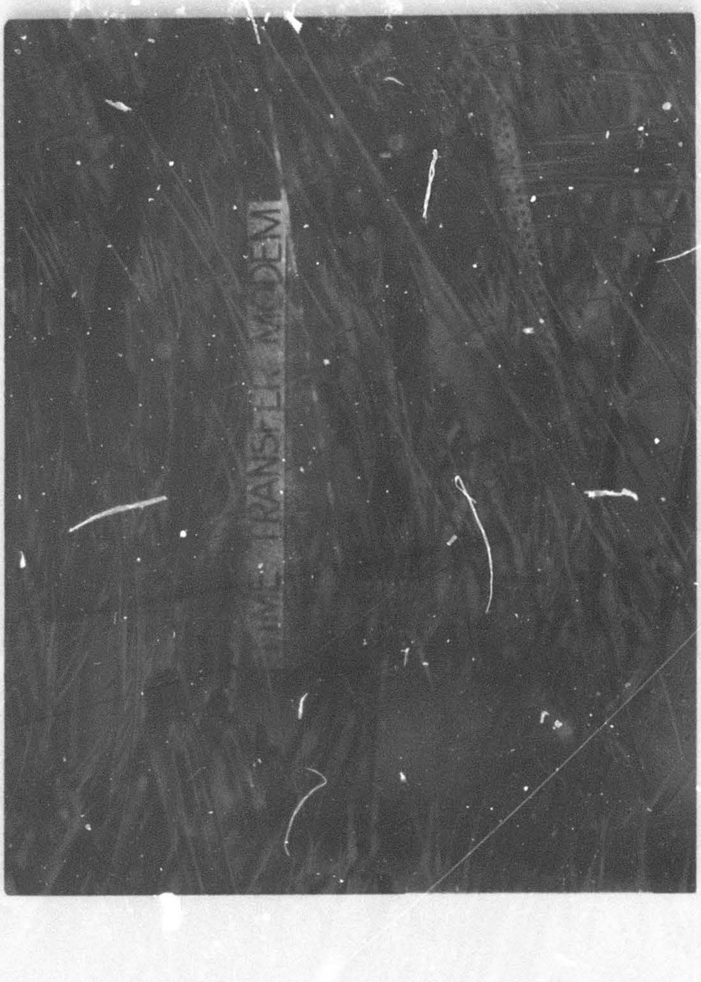
When the phase of the received signal is inverted for a whole code cycle to designate the time tick, the phase-reversal detector of the receiver detects the change and its filtered output gates the designated all-one's pulse from the code generator to represent the received tick. The phase-reversal detector consists of a slow-acting locked oscillator and phase detector to compare the intermediate-frequency signal with the oscillator.

The time-transfer modem pictured in Figure 10 is capable of operation in the presence of interfering pseudo-random or frequency-modulated signals 20 db stronger than the desired signal. Range measurements were made at Helemano, Hawaii, under normal communications conditions with the modem power reduced approximately 15 to 20 db below the station communications channel power.

RESULTS OF TIME-TRANSFER MODEM EXPERIMENTS

The modem was used in a single-access ranging mode at the TSC-54 terminal at Brandywine, Maryland, with as little as 100 w of RF power. The TSC-54 is a transportable terminal employing a relatively small antenna. Late in October a time transfer was made from the Brandywine TSC-54 to the Waldorf, Maryland, NRL satellite communications facility (see Figure 11). Although the distance between sites is an unimpressive 10 miles, the test was useful both to check out the modem and to evaluate the accuracy of time transfers in general.

The total propagation distances actually involved were as large as those for more widely separated terminals, and satellite motion and other


TRANSFER MODEM

TIME TRANSFER EXPERIMENT

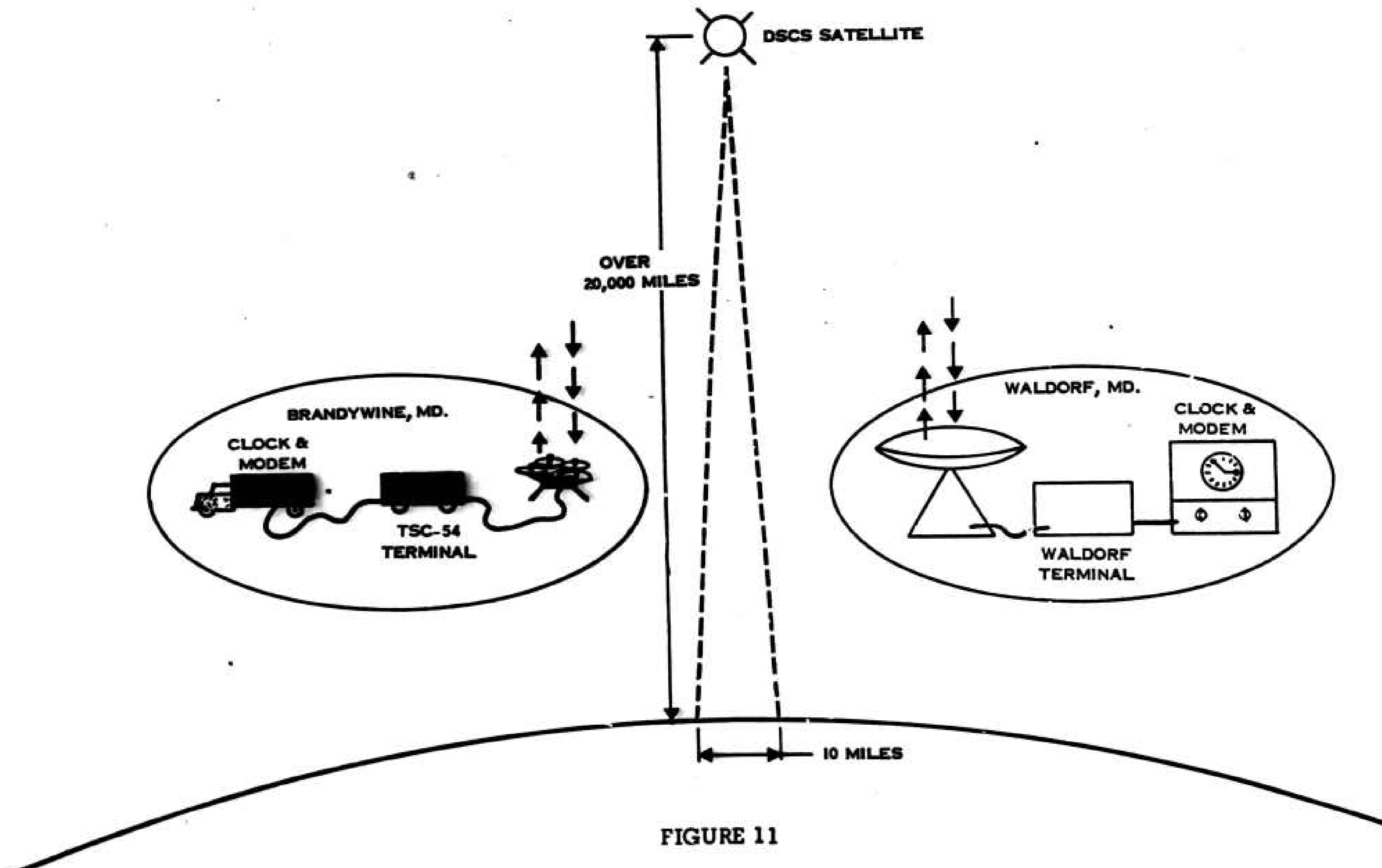


FIGURE 11

factors were believed to be typical. The advantage of using nearby terminals is that the accuracy of the time transfer can be checked reliably.

At each terminal a cesium-beam clock, a time-transfer unit, and a time-transfer modem were used. However, the equipment for the Brandywine site was mounted in a truck equipped with a 115-v AC generator. Only the receive and transmit 70-MHz RF lines of the modem were connected to the TSC-54 equipment. After the time transfer was completed, the truck was driven to Waldorf and the clocks were compared directly.

Figure 12 shows the result of the comparisons between the clocks at Brandywine and the clocks at Waldorf. The spread is typical of transfers made at other locations.

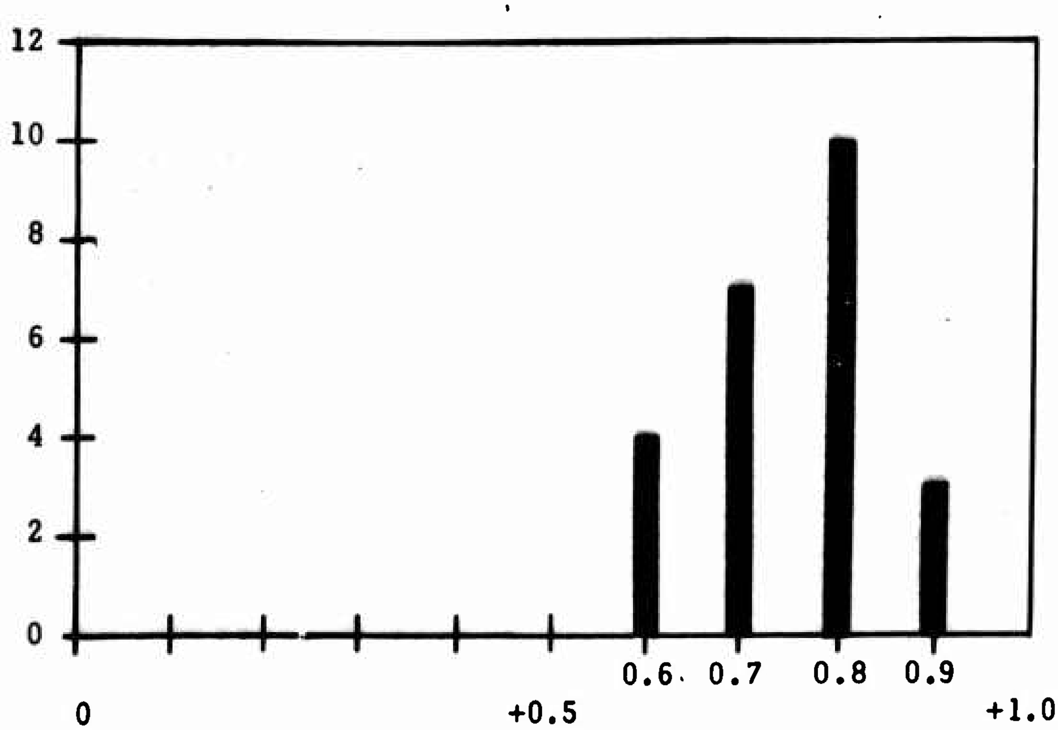
When the direct clock comparison was made at Waldorf, the indicated difference was 0.6 μsec. This would indicate a 0.15 μsec discrepancy with respect to the average of the transfer readings. There is reason to believe, however, that the disagreement is actually less than that. The 0.6 μsec figure was based on a single reading, but a series of clock comparisons made after returning both clocks to the Laboratory about one hour later, indicated that the clocks were approximately 0.7 μsec apart.

It can be readily concluded that the accuracy of satellite time transfer is within the ability of our present equipment to discern. It is thought that an improvement in resolution obtained by using a higher counting rate in the time-transfer unit would result in greater accuracy. But it will be most difficult to prove because equal or better methods are not available.

IMMEDIATE APPLICATIONS OF TECHNIQUE

With equipment already developed it is practicable to provide Observatory time to within a small fraction of a microsecond to a number

RESULTS OF TIME-TRANSFER MODEM TESTS
BRANDYWINE, MD. (TSC-54 TERMINAL) TO WALDORF, MD.



Waldorf Clock - Brandywine Clock (microseconds)

28 October 1970

FIGURE 12

of strategically situated areas. This can be done by equipping certain SATCOM stations with a time-reference facility. The difference between the two forms of this facility (illustrated in Figure 13) is simply the addition of a time-transfer modem in station pairs not equipped with communications modems.

It is not possible to communicate directly with all satellite terminals from any one station. In some cases it will be necessary to relay the time reference over two or more hops, as in the case of Australia's North West Cape (see Figure 14).

The larger (MSC-46) SATCOM terminal at Brandywine will soon be equipped with time-transfer equipment. Shortly thereafter, the time reference will be extended to Hawaii, Guam, or North West Cape, and Germany. Eight or more terminals are expected to constitute the beginnings of the satellite precise-time-distribution network.

PRECISE TIME REFERENCE FACILITY

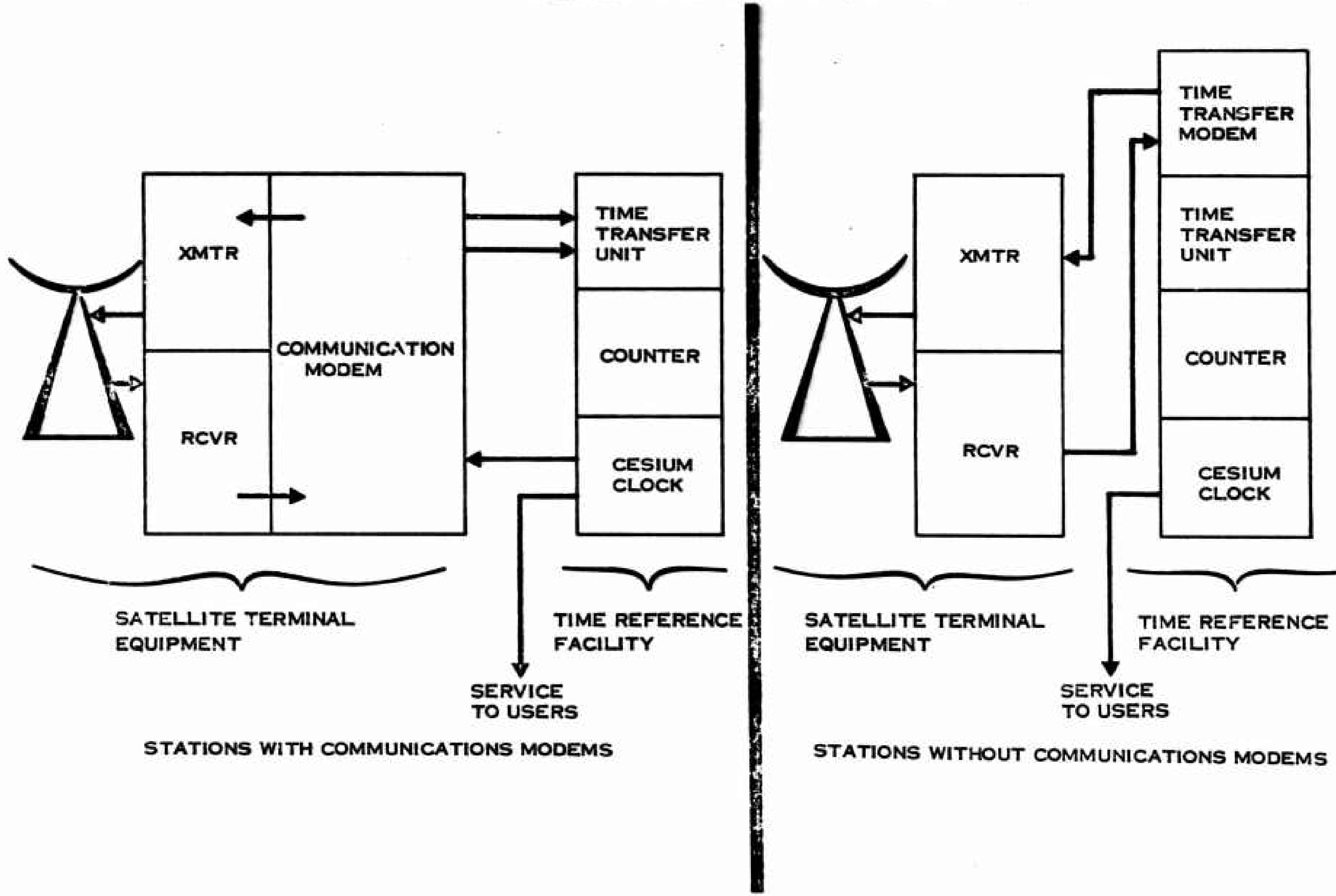
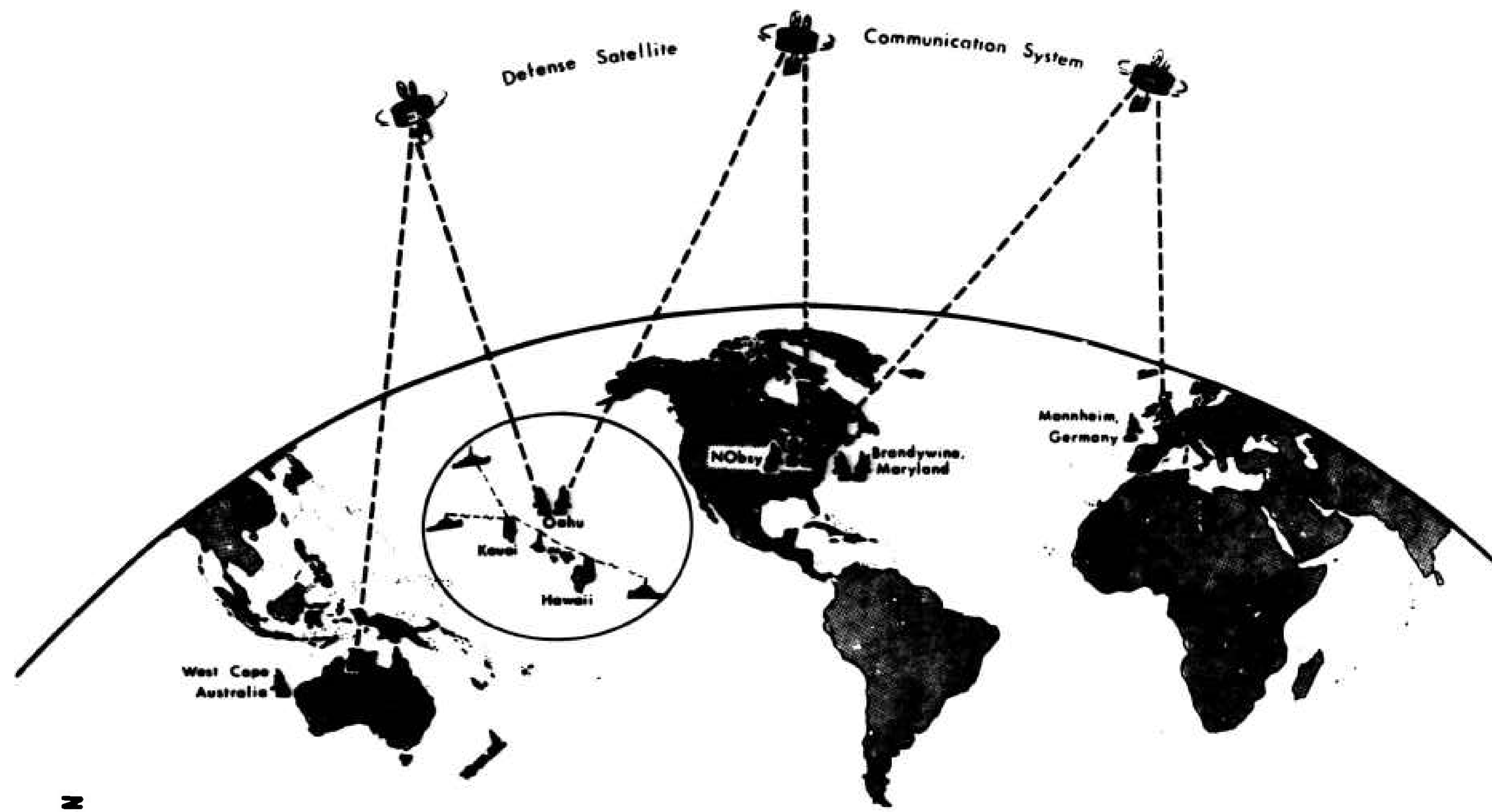


FIGURE 13



PRECISE TIME AND TIME INTERVAL (PTTI) — WORLD DISSEMINATION

FIGURE 14

RECENT VHF/UHF SATELLITE TIMING EXPERIMENTS AT THE NATIONAL BUREAU OF STANDARDS

by G. Kamas and D.W. Hanson*

GENERAL

The work to be described is concerned with satellite timing systems that would serve a large number of users. This is in contrast to other types of time systems that involve a very small number of users. The work referenced here has been published [1,2] or is in the process of publication [3,4]. For those who are interested, copies may be obtained of the published material upon request. This work has been supported by the Air Force Cambridge Research Laboratory.

CURRENT PROGRAM

The current satellite timing research program at the National Bureau of Standards (NBS) has been in progress for about four years and is part of a continuing program to examine useful ways of disseminating time and frequency, useful meaning that the end product must be applicable to a large number of users.

The NBS goal in satellite timing has been to obtain a relatively inexpensive, simple-to-operate, easily understood system. There should be a consistency in the timing system design. That is, the accuracy obtained should be consistent with the cost, the amount of effort expended, and the amount of time the user must wait to obtain the answer. This general approach is often discussed in literature dealing with time dissemination in general. The usual tradeoffs discussed are between ambiguity and precision.

---

*Time and Frequency Division, National Bureau of Standards, Boulder, Colorado 80302, (303) 447-1000, Ext. 3378.

ENVIRONMENT DESIGN

Experiments have been conducted on the NASA-ATS satellites, the Lincoln Laboratories LES-6, and the military TACSAT satellite, all of which were in geostationary orbits. These satellites operated at frequencies in the range of 100 to 300 MHz. These characteristics permit the use of relatively small "TV like" antennas. For each of the satellites mentioned, the signal level was high enough to produce a good signal-to-noise ratio at the receiver.

The system operates as follows. The satellite transponds signals sent from the master station and the several user stations receive the satellite signal. Notice that the satellite itself has no clock or oscillator on board, it simply retransmits whatever it receives. The signal transmitted from the master station is a series of sine wave tone "bursts." These are sent at rates of 1 pps, 10 pps, 100 pps, 1000 pps and finally a continuous tone of 10 KHz. The user station receives these tones, measures their phase shift relative to derived tones from his clock, and computes the total delay. By subtracting the known path delay, it is possible to compute the clock difference. This entire operation is very simple and can be done repeatedly to ensure accuracy. The receiver equipment cost is estimated as $500.

The maximum ambiguity resolved is 1 pps. To obtain time more coarsely, the user needs to know the time to the nearest second (from WWV or other method). The ambiguity could easily be resolved by using the satellite to relay voice announcements of minutes, hours, and days.

The limiting factor in timing accuracy is a knowledge of the total system delay. The motion of even a geostationary satellite is large enough to cause significant timing errors.

The satellite timing error contributed by lack of knowledge of exact satellite position can be very large. To compute its position, the satellite orbital elements should be used. Most satellites are "ranged" by their respective operating agencies at frequent intervals, but unfortunately, experience has shown us that (except in special cases) most satellite positions are not known with sufficient accuracy for the needs of time dissemination. Several methods have been tried to circumvent this problem. One, the timing accuracy of the system has been carefully checked immediately after a ranging measurement and the daily increase in error has been noticed from that time until the next range measurement. Two, the timing stations have been used as a point where the time is known and the results from the timing signals used to "range" the satellite have produced great success. By this second method of subsequent timing measurements, the results are much improved.

The stations used in the NBS experiments were in Massachusetts; Boulder, Colorado; Ohio; and South America. Each station maintained accurate time using a cesium standard. Under the best conditions, the results approached an accuracy of 40 μsecs. However, when the satellite had not been ranged for some weeks, the accuracy was about 150 μsecs.

PLANS FOR FUTURE SERVICE

Based upon what has been learned from experiments to date, NBS has concluded that a satellite timing service is possible in a few years. This service would meet the criteria mentioned -- simple operation, low user cost, and an accuracy of about 10 μsecs. The customer would be expected to have receiving equipment, a divider with coherent outputs, and an oscilloscope; the operation would most likely be manual. If it were possible to use voice transmission over the satellite, the problem of time ambiguity could be resolved by sending time announcements, similar to those of WWV.

SUMMARY

The work described here has shown that a satellite timing system can be implemented at very low user cost. The best accuracy obtained is about 40 μsecs. This figure can be improved by a simple and practical modification of the standard technique. Most important, the user cost and time involvement is proportional to the accuracy requirement. Thus, the recent experiments at the NBS on VHF/UHF satellite timing indicate that a future service is both possible and practical.

REFERENCES

[1] J.L. Jespersen, G. Kamas, L.E. Gatterer, and P.F. MacDoran, "Satellite VHF Transponder Time Synchronization," Proc. IEEE, Vol. 56, No. 7, 1202-1206, July 1968.

[2] L.E. Gatterer, P.W. Bottone, and A.H. Morgan, "Worldwide Clock Synchronization Using a Synchonous Satellite," IEEE Trans. Instrumentation and Measurement, Vol. IM-17, No. 4, 372-373, December 1968.

[3] D.W. Hanson and W.F. Hamilton, "Satellite Tracking for Clock Synchronization," (to be published).

[4] D.W. Hanson and W.F. Hamilton, "One-Way Time Synchronization Via Geostationary Satellites at UHF," (to be published).

621B SATELLITE SYSTEM - ABSTRACT

Lieutenant Colonel J. A. Fiebelkorn*

The 621B Satellite System was developed as a real time position location system, not for the purpose of disseminating time. However, one of the results of a concept formulation study was the realization that real time implied a degree of time synchronization which had not been previously achieved. A concept for continuous resynchronization would offer the capability to transfer time as well as to establish position. Precise time dissemination to less than one part in 10^7 is possible for equipped users within the current state-of-the-art using the 621B Satellite System. The cost of such a system would be such that it would be uneconomical to deploy it exclusively for time dissemination; however, should the system deploy precise time transfer, it would be available to all users.

This report is classified SECRET and is in Volume II of the conference report. It can be obtained only by written request to the U.S. Naval Observatory, Technical Officer, Washington, D.C. 20390.

---

*Project Officer, Policy and Plans Group, U.S. Air Force Headquarters, Washington, D.C., (202) OX 5-4062.

PRESENTATIONS BY

Mr. Lauren J. Rueger

Mr. Roger L. Easton

Dr. G. M. R. Winkler

Dr. Walter H. Higa and Mr. Samuel C. Ward

Mr. George Kamas

Mr. Robert Stone

TRANSIT NAVIGATION SATELLITE

by Lauren J. Rueger*

The Applied Physics Laboratory has nothing particularly spectacular to offer in the form of time transfer; however, the navigation satellite system has provided precision time from the beginning. The concept on which the system was based was formulated about 1960 and has a timing requirement--specifically, a self-consistent time synchronization between the satellite and the ground system. This synchronization must be within 2 msecs. The navigator who uses the system can have timing errors up to about 30 seconds, which cause no inconvenience, and even errors up to 15 minutes can be handled.

The carrier frequencies to the system are important, and in the signal frequency measurements, the satellite and the navigating equipment must have local-oscillator frequency stabilities which do not depart by more than one part in 10^9 over the observation period. A correlation has been established between time/frequency errors and navigation accuracy. The relation is very nearly a linear function of the frequency and time errors. The proportional constants are 1/10 of a nautical mile error for a frequency disturbance of one part in 10^9 during the observation time, and a .004 nautical mile error for a timing error of 1 msec. The timing error corresponds directly to the distance traveled by the satellite which is moving at about 7 meters per millisecond.

This paper will present data to support the claim of 10 μsecs time synchronization with equipment for this program. The program also has

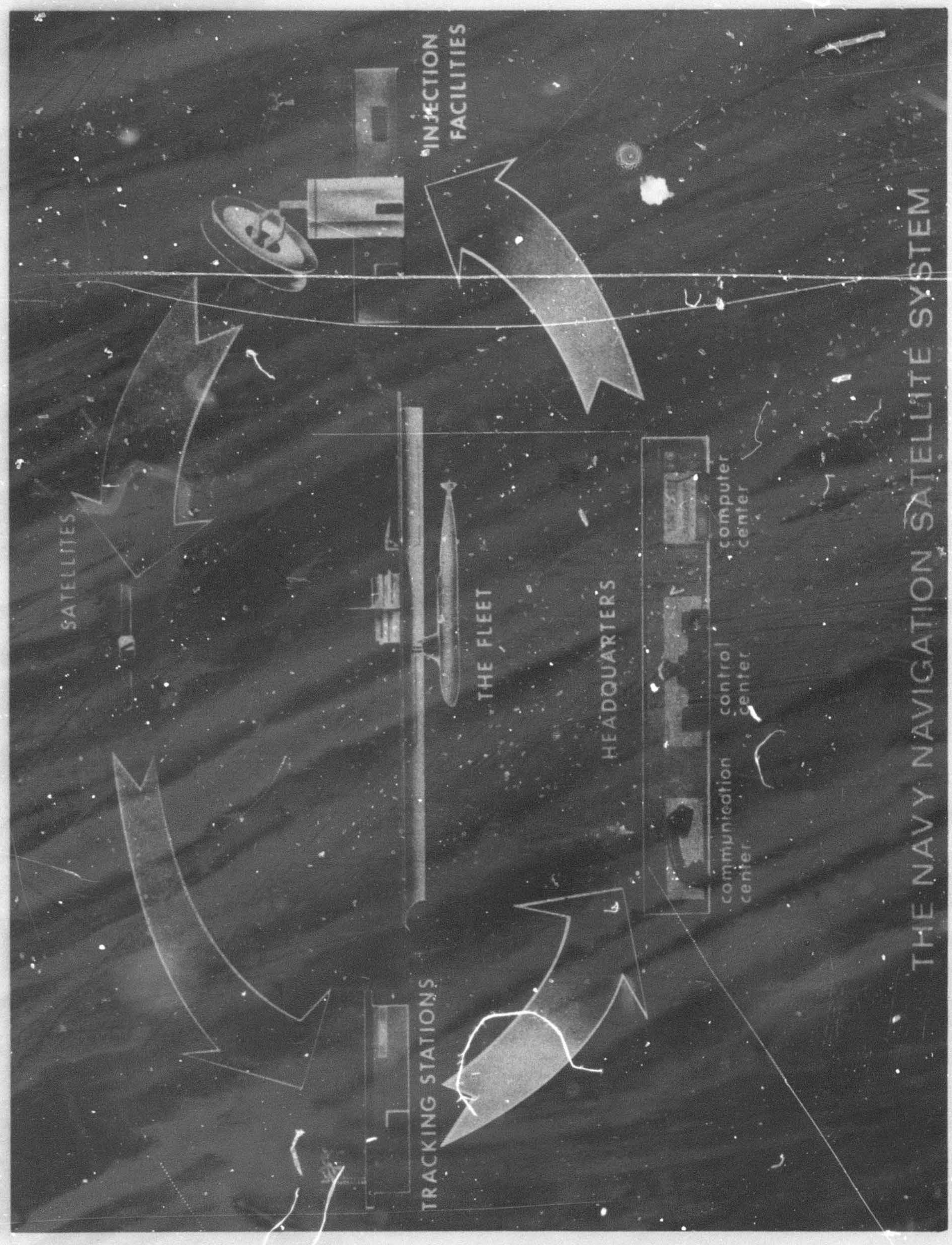
*NAVSAT Project Scientist, Applied Physics Laboratory, Silver Spring, Maryland, 20910 (301) 953-7100.

in-orbit reference oscillator stability performance of better than one part in 10^9 over an interval of 100 days, or better than one part in 10^{11} oscillator stability per day. Figures are included to explain how the system works.

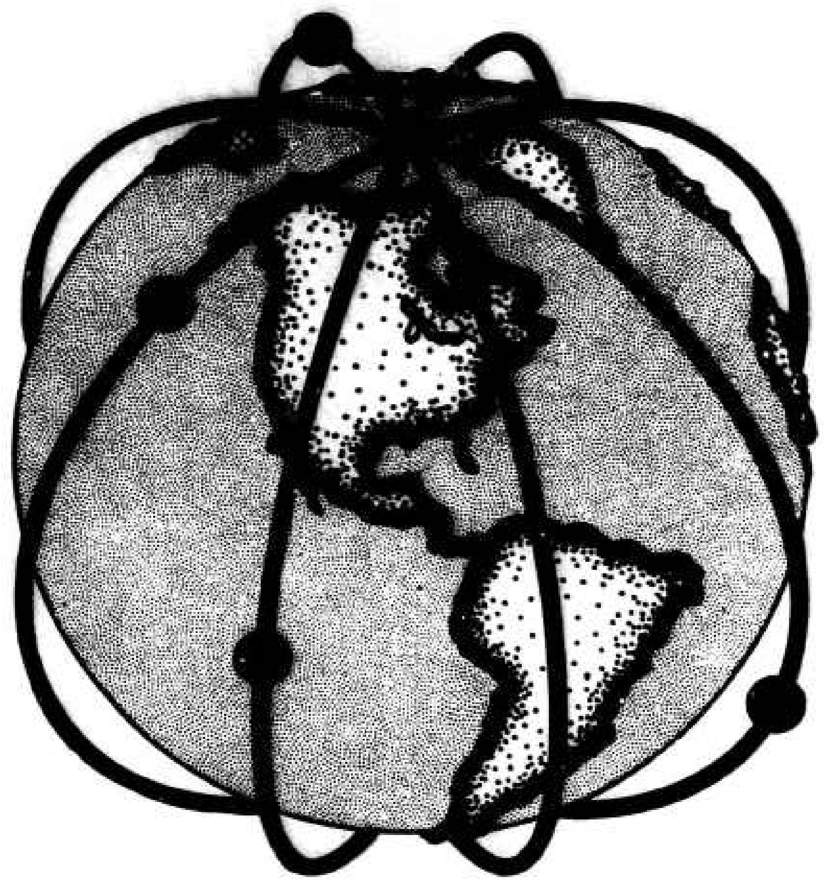
The circle can be entered (see Figure 1) at any selected place. Once the satellite is in orbit, it transmits on 150 to 400 mc, a crystal stabilized signal, which is picked up by ground tracking stations. These are located on U.S. territory. Records are kept of the frequency transmitted by the satellite as a function of time and are then transmitted to headquarters, where a central computer determines where the satellite has been traveling and predicts where it will be in the next 16 hours. That information then is injected by a signal from a ground-based transmitter into the satellite, and the satellite stores its predicted orbit for the next 16 hours. The satellite then transmits its position in a simple Kepler coordinate system plus small 3-D corrections. A navigator uses the system by recovering the orbit data from the satellite and measuring the doppler shift of the carriers. By knowing where the satellite is located, from the orbit data, and determining the geometry between the satellite and navigator from the doppler, it is possible to get a navigation fix.

Figure 2 is a picture of one of these satellites. It is not a very pretentious device--it weighs about 112 pounds when deployed in orbit; gets its power from solar cells that charge batteries; and uses a circularly polarized antenna, so that a very simple non-directional whip antenna can be used for ground-based reception. The directional antenna is aimed at the earth because there is a pendulum that makes it hang in space. It is a gravity gradient stabilized satellite.

The concept of how the orbits are planned is shown in Figure 3. Any one of the satellites serves the entire world. These satellites are 600 miles above the earth and are in nearly circular polar orbits. They


THE NAVY NAVIGATION SATELLITE SYSTEM
SATELLITES
INJECTION FACILITIES
THE FLEET
HEADQUARTERS
communication center
control center
computer center
TRACKING STATIONS

NAVIGATIONAL SATELLITE SYSTEM



FOUR POLAR ORBITS

REV. APR. 1963

were planned to be about 45 degrees apart around the equator, but since some of these have had long service lives and were not launced into the exact polar plane,they have precessed away from the 45-degree separations. There are five in service at the present time.

Basically, Figure 4 shows what each of the satellites contains. This is a crystal oscillator and a double-proportional oven; it is a fifth overtone, 5-mc crystal, from which both the time system and the carriers are derived. This is the receiver that stores in its memory the location of the satellite. It is binary digitally encoded data that phase-modulates the carriers.

From the very start, precision time has been provided as a service. There is not an established requirement that it be UTC, however, because to use the system, the navigators do not have to synchronize to anything but system-time. Time is recovered from the satellite from a unique signal that is transmitted about every two minutes. Navigation is performed on the basis of time kept by the satellite.

Figure 5 shows the diversity that the program has undertaken in its years of service. It started off as a navigation aid to the POLARIS submarine. The instrumentation includes a receiver, a computer, and a lot of peripheral gear to keep records, as well as to make the computer programming more sophisticated as the geodetic knowledge expands. The Laboratory developed a small unit for the surface equipment which has been used for over five years by surface units. The military version is just taking its place this year. The satellite navigation program got off on some tangents because it was found that the earth really was not well enough defined in the geodetic form for an observer to tell precisely where a satellite was going to be in the future. The geodetic program requires data from many locations. The figure shows a very small receiver for taking geodetic-type information, suitable for operation anywhere in the world for good surveying data. Also on the figure is a piece of back-track

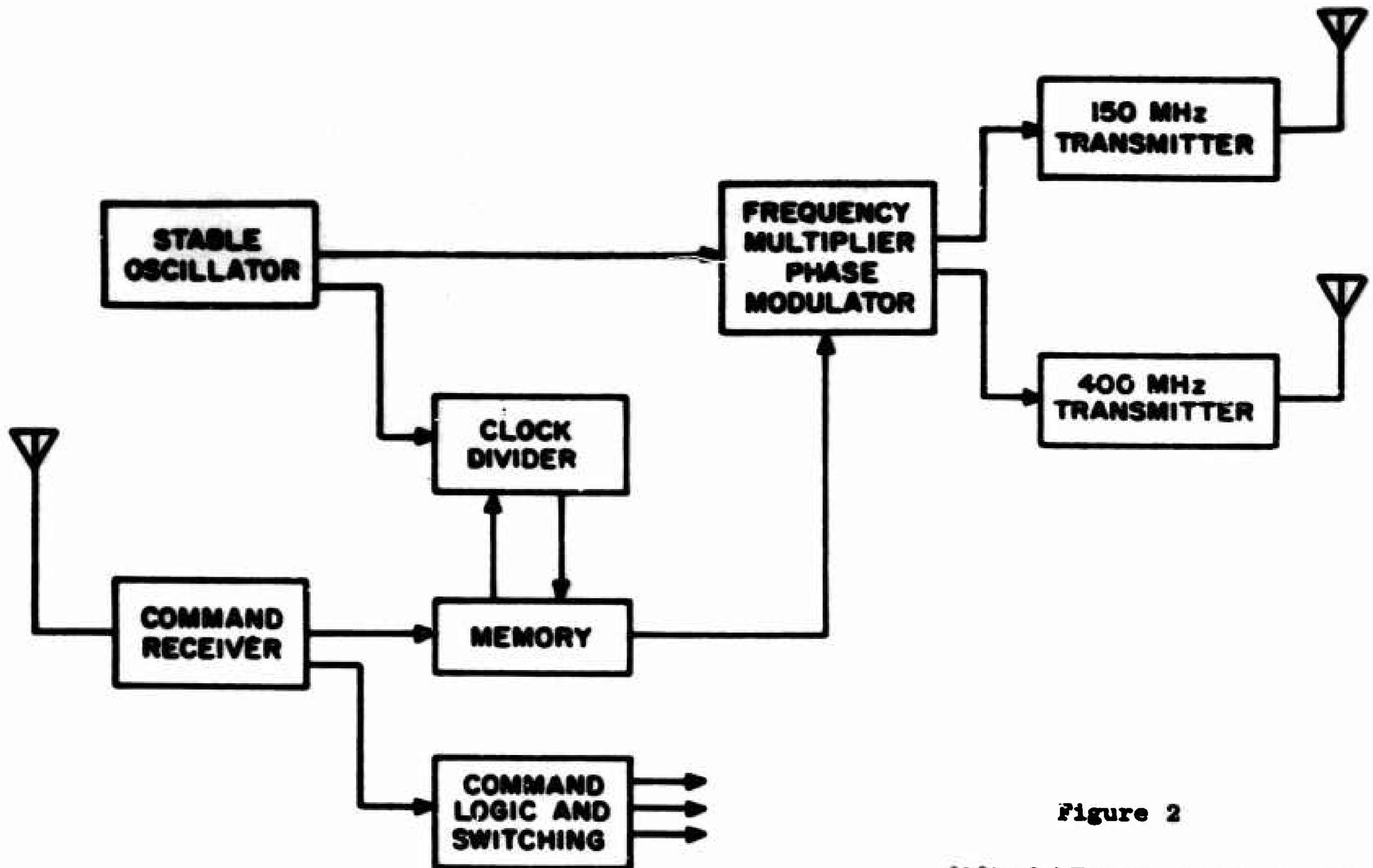


Figure 2

NAVIGATION SATELLITE BLOCK DIAGRAM

NOT REPRODUCIBLE

equipment so small that people can take their positions on a man-portable set. These things are real hardware; they work, but they are not yet available in large quantities. This geodetic effort turned out to be more significant than the Laboratory expected.

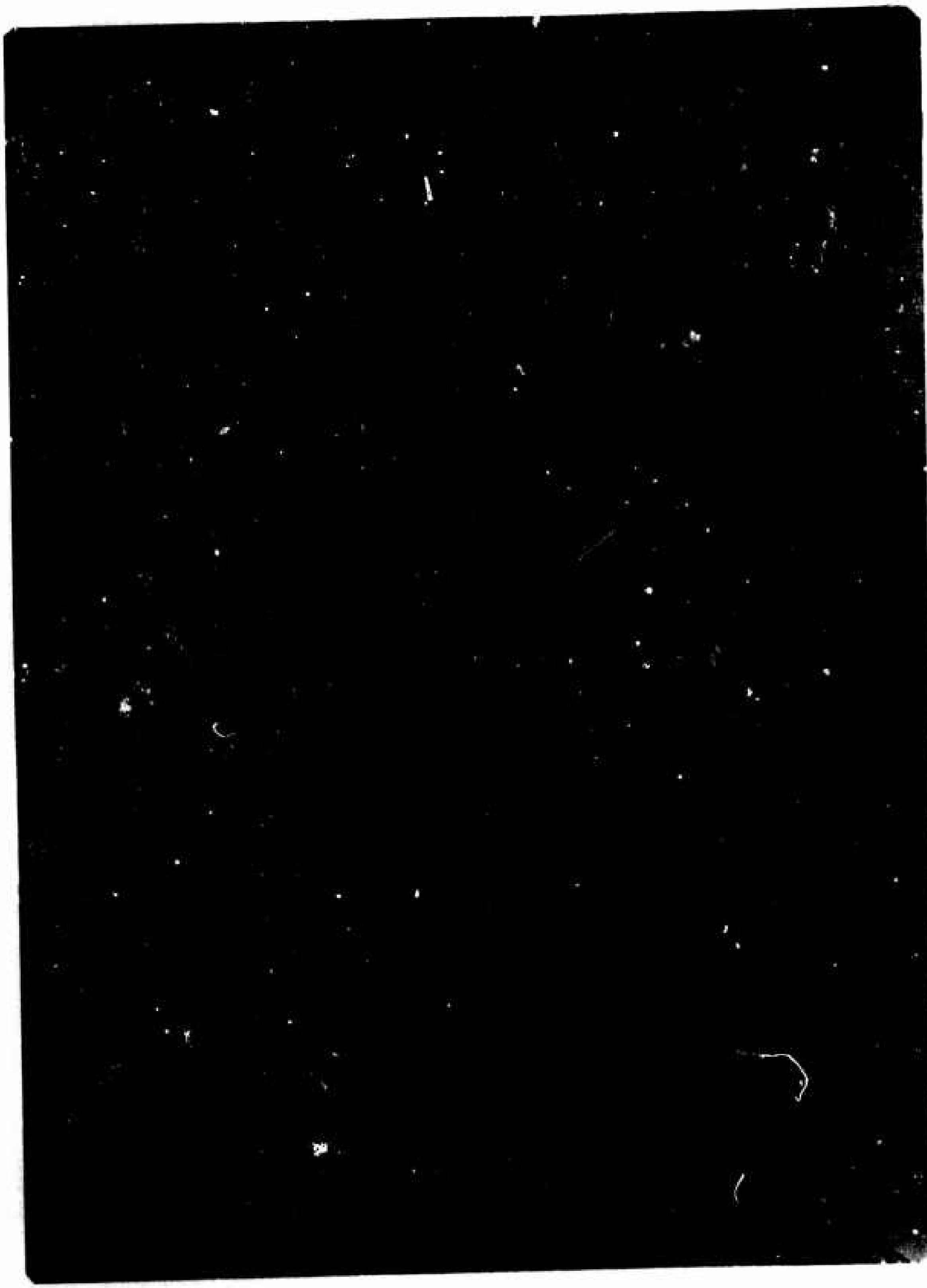
Figure 6 shows what was found out about the earth--it really is not round any more. If you describe the earth from the mathematical function as an oblate spheroid, the little contours represent about 10-meter departures from that mathematical function. This type of information was essential in order to realize the kind of precision that is being obtained from the navigation system. It was necessary to set up a world-wide tracking network to keep track of the very small permutations of the orbit as the satellite went around the earth.

Figure 7 shows the positions of stations operated in support of this work. There are about 12 permanently located stations which have been in service for periods longer than five years, and which generate the data base that has been acquired by tracking satellites. Satellites in orbits of different inclinations and altitudes have provided the data base on which the present world geodesy is formulated.

Figure 8 lists the stations which have station numbers assigned to them. This gives an idea of the timing residuals received in some of the stations in their time synchronization on a routine basis. (This happens to be for the month of April for one of the operational navigation satellites.)

The observers take a number of timing data points each time the satellite goes by, and then they compute the rms residual of that group of points, (e.g., for two satellite passes, the rms errors were 10 μsecs or less for station 008; that station is located in Brazil). The local station in Howard County, station 111, is one of the better frequency and time control stations, and these measurements show that the timing residuals are very low. One of the operational stations, station 330, which is operated by

NOT REPRODUCIBLE



NOT REPRODUCIBLE

DISTRIBUTION OF APL TIMING RESIDUAL RMS FOR
SATELLITE 1967-92A, 1-30 APRIL 1970

Sta- tion	RMS (Milliseconds) .01	.02	.03	.04.	05	.06	.07	.08	.09	.10	.11	.12	.13	.14	.15*	Total
008	2	1		2	3											8
013	1	2	2	4	1											10
014	10	7	1	1												19
018	5	11	14	17	8	5	2	1		2					1	66
019	5	20	21	11	4	1	1									63
020	4	4	5		1											14
103	7	6	5		1											19
106	5	1	7	4	4	2										23
111	20	3														23
112	1	4	12	5		1										23
115	1	6	7		2											16
117	2	6	5	2	1			1								17
121	3	5	3	5	2											18
330	16															16
700			1													1
733	12	1														13
765	1	2	5	4	2	3		1								18
766	1	1	4		2											8
895			2	1		1	3	2								9
896	12	19	8	6												45
898		4	3	6	6	4	1	1		1						26
911	5	2														7

*0.15 or over.

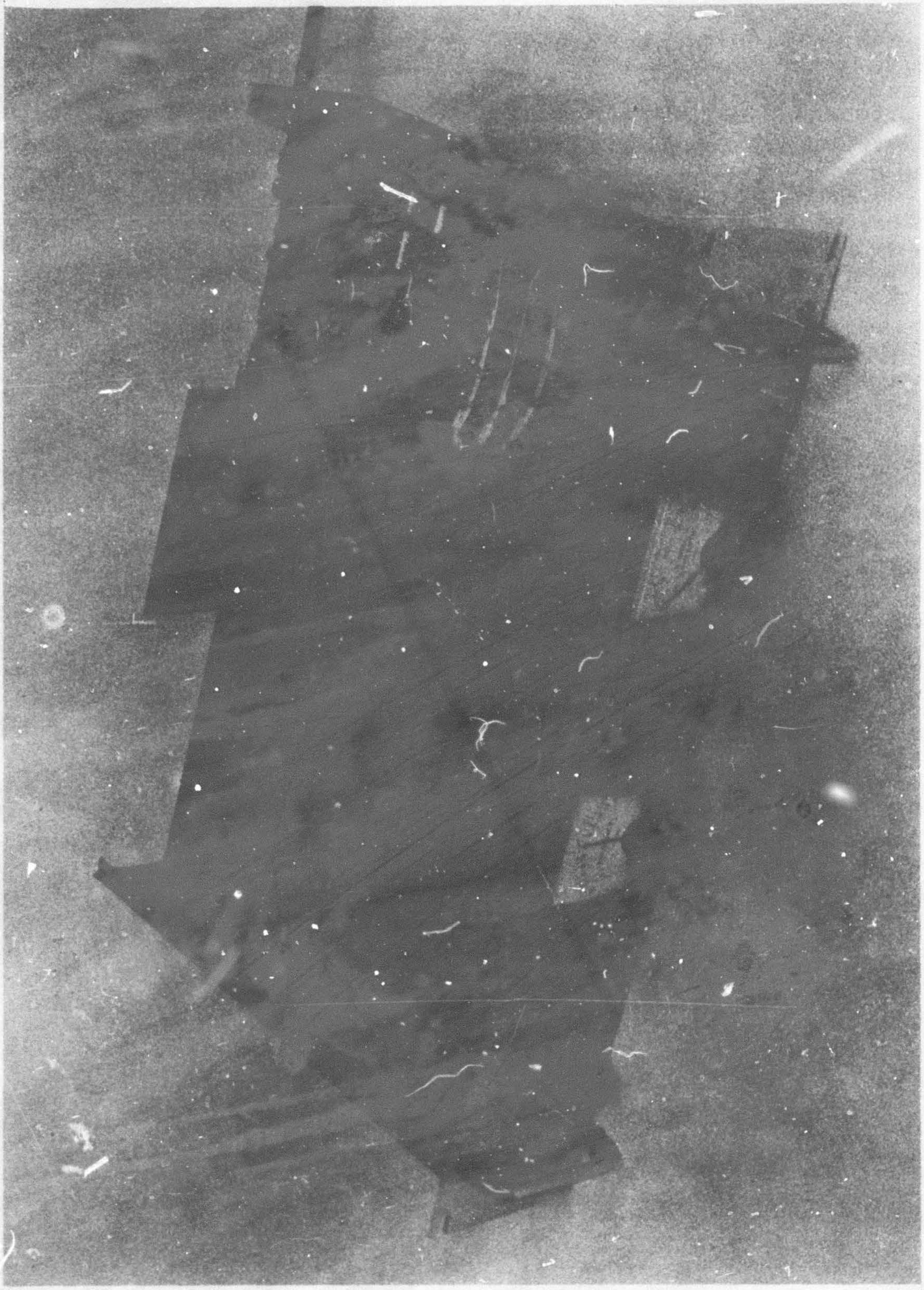
the Navy on the West Coast, is shown on the figure. Others are located in various places, such as Australia 112, 115 in South Africa, and 117 in the Seychelles.

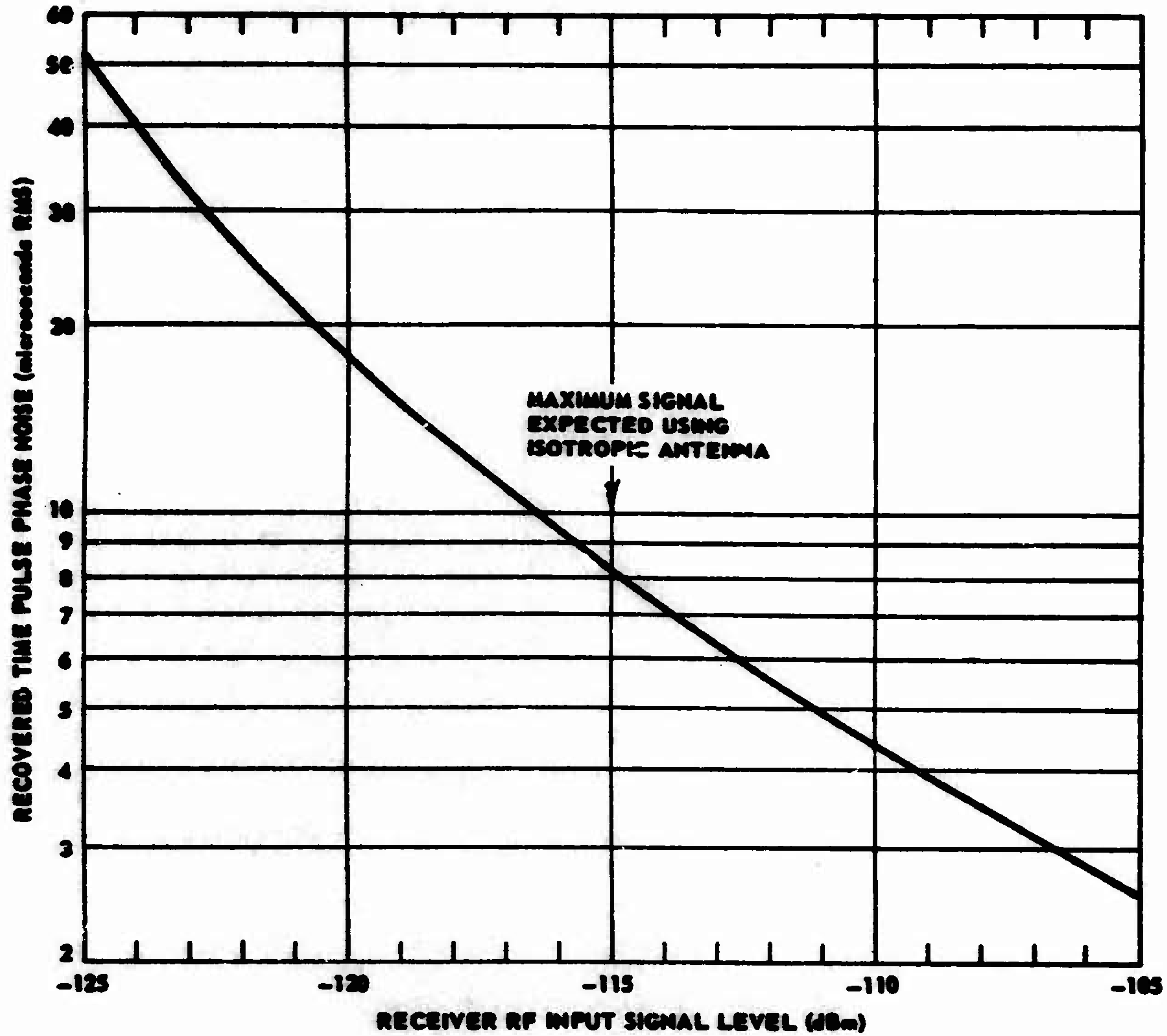
The people operating the tracking station at the APL site have had to be on duty 24 hours a day, 7 days a week, so they have had some spare time on their hands. These operators worked up a design for a satellite time recovery receiver that is quite small. Figure 9 is a picture of one of these units, however, it does not represent a state-of-the-art engineering effort.

Figure 10 shows the inside of the satellite time recovery receiver, which is a tracking filter-type receiver at 400 MHz, and some digital logic. These are integrated circuits, TO-5 cans, and also a power supply.

Figure 11 shows the performance that is being realized by this instrument. The phase noise in the receiver is plotted as a function of signal-noise signal-level. It operates normally on a non-directional antenna. Normal satellite signal levels are about -115 db which represents an instrumentation error of about 8 μsecs in time recovery by this instrument.

Figure 12 shows some of the pertinent parameters regarding the model shown in the previous figures. This data relates to the first model built. There is an improved model that has little better signal-noise ratio and an instrumentation error of about 5 μsecs. The signal is at a frequency of 400 mc -80 parts per million and has a doppler shift of $\pm$ two parts in 10^5. The phase-locked loop in this unit is 15 cycles wide and the timing output is a 10-volt spike with a 2/10 μsec rise time. It occupies 3½ inches of panel space, weighs 15 pounds, and uses 10 watts average power. APL is not in a position to manufacture these items in quantity, so the Coast Guard has put in an order to a small company in the Annapolis area for a quantity of ten. They sell for about $2500.





NAVIGATION SATELLITE TIME RECOVERY RECEIVER FIDUCIAL
TIME RECOVERY PHASE NOISE

NAVIGATION SATELLITE TIME RECOVERY RECEIVER

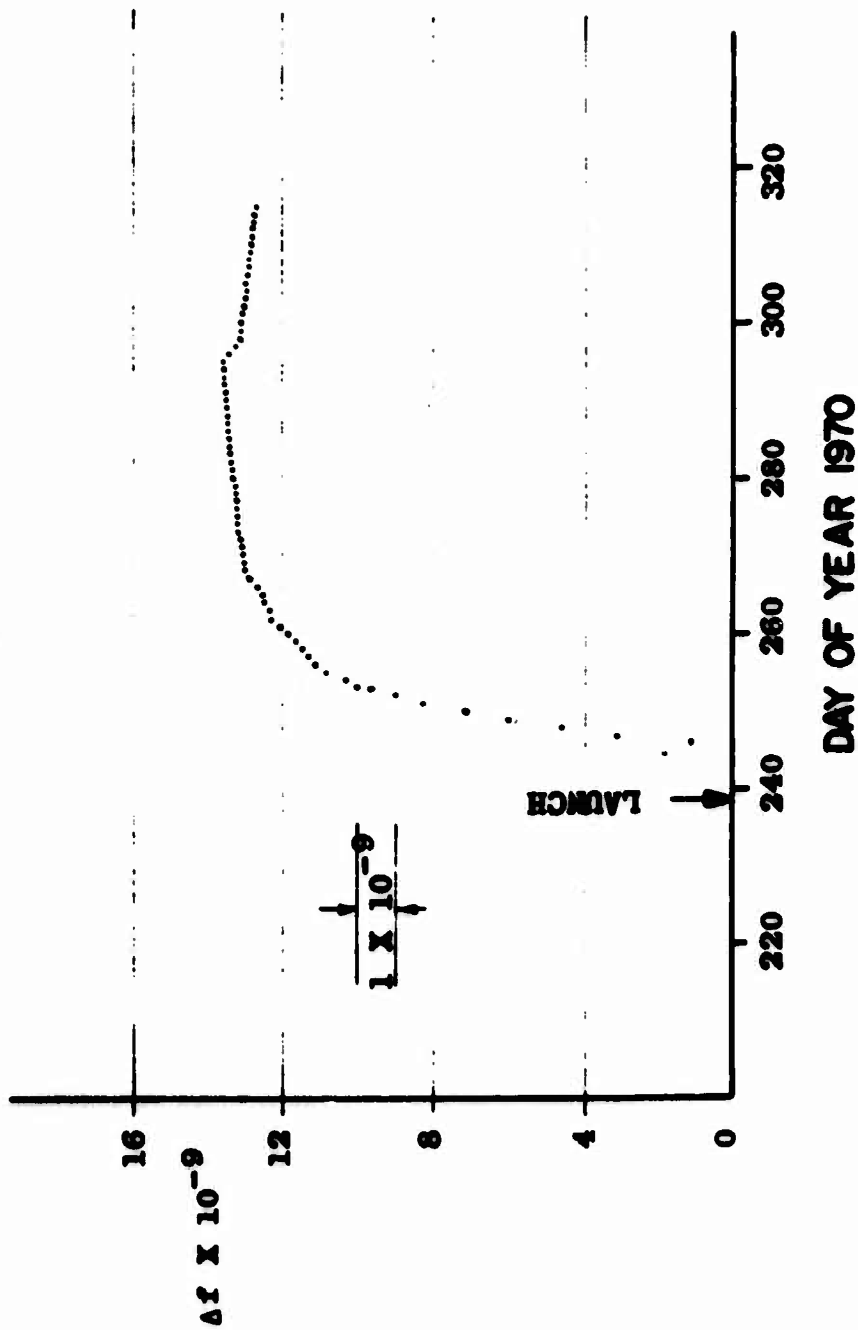
1. FIRST MODEL: 8 μ second rms @ -115 dbm SIGNAL/NOISE = 6 db
2. SECOND MODEL: 5 μ second rms @ -115 dbm SIGNAL/NOISE = 3 db
3. OPERATING FREQUENCY: 400 MHz - 80 PPM ($\pm 2 \times 10^{-5}$ DOPPLER)
4. INFORMATION BANDWIDTH OF PHASE LOCKED LOOP: 15 Hz
5. OUTPUT: PULSE - 10 VOLTS WITH 0.2 μ second RISE TIME EVERY 2 MINUTES
6. SIZE: 3½" PANEL SPACE; 19" RELAY RACK WIDTH; 15 POUNDS
7. POWER: 10 WATTS @ 60 ~
8. COST: ABOUT $ 2500 IN QUANTITIES OF TEN

Figure 13 shows an example of the frequency stability in one of the satellites from launch time. The days at the bottom represent the calendar year of 1970, and the scale of the frequency resolution of the chart, one part in 10^9 is as indicated. A satellite was launched the last part of August, and within two or three days, it was ready to be used. These measurements are one day apart. Since navigation is possible when the frequency error is less than one part in 10^9 over a 10 to 15 minute period, it is seen from this data that navigation quality operation is attained 12 to 16 hours after launch. Note that by 10 or 15 days later, the stabilities are well below one part in 10^{10} per day.

Figure 14 shows an oscillator which has been operating in the same time period. As a matter of fact, that is the slowest drifting oscillator APL has in orbit. This has been in service three years, and you can see a change for 100 days of less than one part in 10^9. The instrumentation for measuring includes an iterative fitting routine with a measurement sensitivity of two parts in 10^{10} on a single measurement.

The Applied Physics Laboratory has been funded to put up another series of satellites. One of the items planned for this series is an improved way of keeping the time to the UTC standard. Presently, time is set in 10-μsec jumps, which seems to be a very generous time resolution for a 2-msec system requirement. Now that needs are developing for a higher resolution, it may be possible to implement some of the ranging propagation approaches which have been previously mentioned. In order to provide a more uniform time scale, a device called an incremental phase shifter is planned for one of these satellites. It is a synthesizer that goes between the oscillator and the input to the timing and transmitting chain. It has two objectives, as shown in Figure 15: (1) to take out the frequency drift that exists in the oscillator, and (2) to adjust the epoch. The initial design for this next satellite will have a course time resolution

SATELLITE 30190
FREQUENCY HISTORY



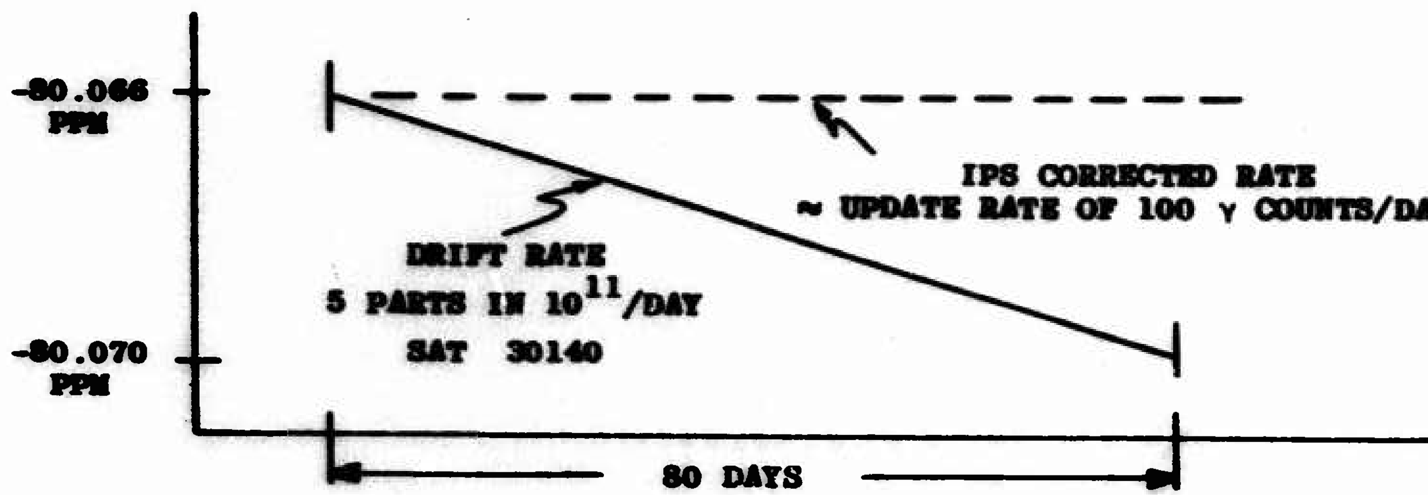
FREQUENCY ADJUSTMENT

TYPICAL SATELLITE OSCILLATOR LONG TERM DRIFT IS PARTS IN 10^{11} PER DAY

IPS SYSTEM RESOLUTION IS:

8 PARTS IN 10^{13} FOR THE 84.48 PPM OFFSET

6 PARTS IN 10^{13} FOR THE 145.51 PPM OFFSET



MAJOR PERFORMANCE CHARACTERISTICS OF THE IPS

THE TWO OBJECTIVES OF THE IPS SYSTEM ARE:

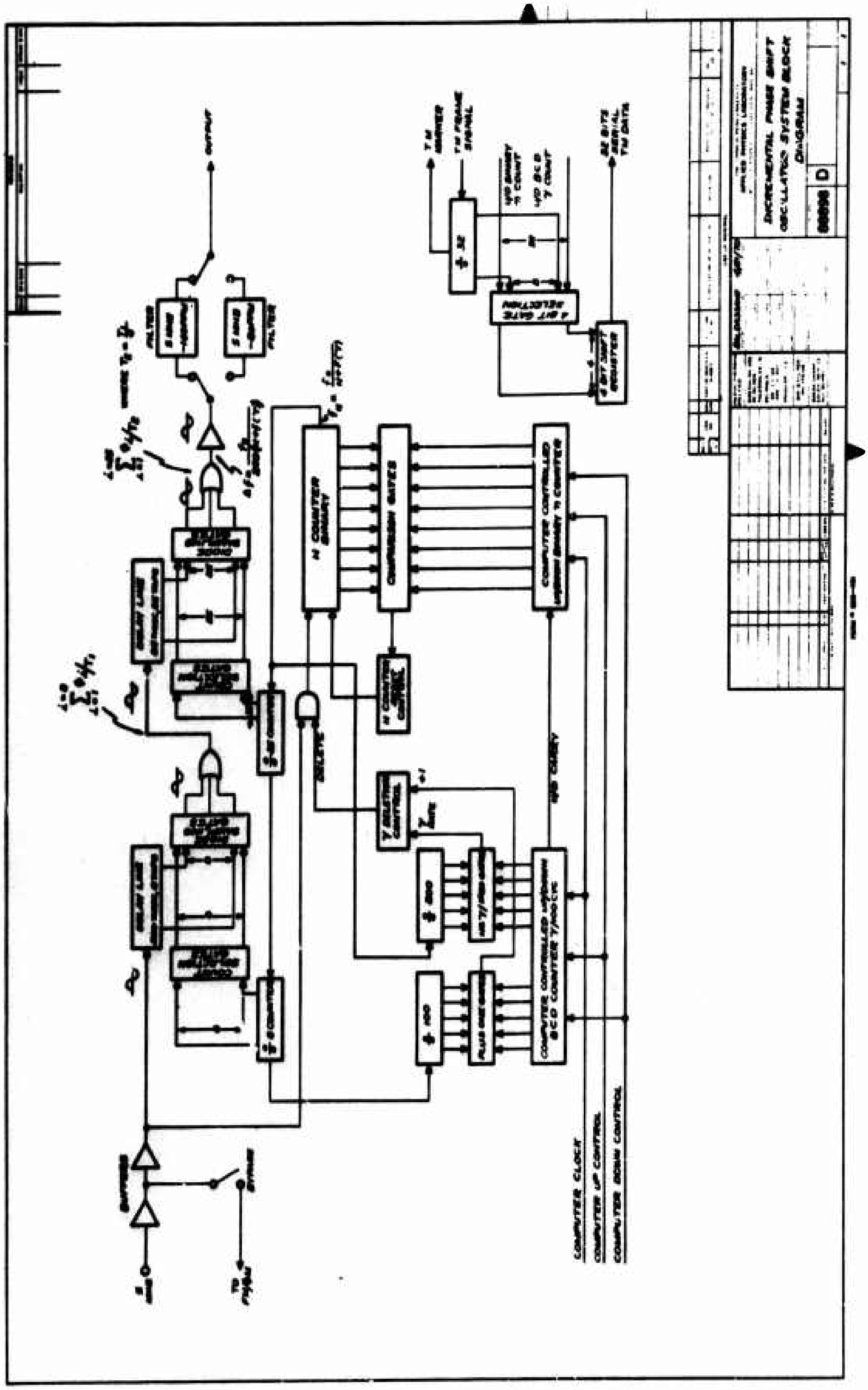
1. TO CORRECT THE LONG TERM FREQUENCY DRIFT OF THE SATELLITE OSCILLATORS (-80 PPM AND -140 PPM) TO A PRECISION OF PARTS IN 10^{13}

2. TO ADJUST EPOCH WITHIN THE PRESENT 200 NANOSECOND WINDOW TO A PRECISION OF ONE NANOSECOND

of 200 nsecs which is the period of one cycle of the 5-mc oscillator. Time adjustments will provide a timing error less than 1 nsec.

The design parameters were picked as shown in Figure 16, to give a resolution of about eight parts in 10^{13} per adjustment step. The phase is shifted continuously to remove the frequency error of the oscillator. Two frequencies will be possible for operating the satellite; one at -145 parts per million for use on an experimental basis and the other at -84.48 parts per million, the operational value. There will be an operational capability in this satellite. The odd offset operational frequency is tied back to the selection of some system parameters--6,103 bits for a two-minute interval works out to provide a simple integer frequency divider chain derived from the offset 5-mc signal.

Figure 17 generally shows how this incremental phase shifting is accomplished. The input oscillator signal goes through a 200-nsec delay line with eight taps, each tap being a step of 25 nsecs in epoch. The analog 5-MHz signal is gated from each tap by diode bridges. This output goes through a 25-nsec delay line with 25 taps. Each of these taps provides a 1-nsec phase adjustment or time adjustment. The gating is also through diodes. Since this jumping between diode switches introduces noise on the signal, the output spectrums must be cleaned up by crystal filtering. These filters can be several hundred cycles wide at the 3 db pass band limits. The transfer function from the input to the output frequency is an exactly known function of the parameters with the known settings of the digital instrumentation which are all going to be set by ground command. As you can see, a signal of 5 mcs comes in and goes into a counter. Every time this counter overflows, it advances the phase shifter 1 nsec. Presently, that counter is run until it reaches a number held in a register. The register will contain a number like 70 to 90 which can be set from the ground. Unfortunately, that does not provide the resolution desired, so a million steps have been provided in another binary


INCREMENTAL PHASE SHIFT OSCILLATOR SYSTEM BLOCK DIAGRAM
N COUNTER BINARY
COMPARISON GATES
COMPUTER CLOCK
COMPUTER UP CONTROL
COMPUTER DOWN CONTROL
OUTPUT

system between each counter integer. One step in this million unit makes a frequency adjustment of eight parts in 10^{13}. The stepping of the fine frequency adjustment will follow a programmed sequence to take out first or second order drift rates of the oscillator. Consequently, counting registers can go up or down to accommodate both up and down drifting oscillators, and each time the one million unit overflows, it moves the course register over one. It is a continuous system. There is no recycling; the system smoothly progresses over its entire adjustment range, advancing with steps of the finest resolution.

With regard to the future requirements for precise time and time interval for the NAVSAT program, APL does not establish any of these requirements. However, if a requirement is established, APL would be most happy to comply with the requirement. APL has a working frequency standard which is now within eight parts in 10^{13} of the Naval Observatory in the UTC time system. The timing epoch at our Laboratory is held within $\frac{1}{2}$ μsec, relative to the Naval Observatory's time system. Common monitoring of the LORAN-C system is being used in order to hold the value. Clock transfers have been provided to establish and calibrate. Synchronization to the Naval Observatory has been done on a routine basis for a good many years. Instrumentation in our own development programs can make synchronization measurements internally to the Laboratory to about 2 nsecs. Some of the receiving instrumentation has been checked out that will provide synchronization measurements of 10 nsecs between roof-mounted antennas and reference signals inside the Laboratory.

TIMATION NAVIGATION SATELLITE - ABSTRACT

Roger L. Easton*

TIMATION is a program in technology leading to a navigation system. The Naval Research Laboratory (NRL) performs theoretical analysis, develops critical components, and performs measurements on satellites as required to define a navigation system to meet classified requirements of the Joint Chiefs of Staff. The critical item in a satellite navigation system is the ground station location, which determines the satellite constellation. At present, navigation fixes, instantaneous fixes, and running fixes have been demonstrated and ionospheric refraction measurements have been made. NRL is presently in the process of using experimental satellites for time synchronization.

This report is classified CONFIDENTIAL, and is in Volume II of the conference proceedings. It can be obtained only by written request to the U.S. Naval Observatory, Technical Officer, Washington, D.C. 20390.

*Research Engineer, Space Technology Division, Naval Research Laboratory, Washington, D.C., (202) 767-2595.

COMMENTS ON NAVSAT TIME DISTRIBUTION

Dr. G.M.R. Winkler*

I would like to make some comments and would speak to the last three presentations which have been made. I think the range is very wide--perhaps between something similar to the ultimate concept, which would give practically everything which you could possibly extract with modern technology (621B), to a system which is operational; and that of course is TRANSIT. Here I feel it is necessary to emphasize the points which are important for our conference. Unfortunately, here in this country, the use of this existing operational system has been minimal for time transfer. However, the French are using it. They use the TRANSIT system to synchronize their stations which are in support of the French satellite ranging research effort, and they report a precision obtained to about 10 μsecs. It is done very simply by using the 2-minute time tick which is emitted by the TRANSIT satellite.

As you will probably recall, the satellite emits a continual code stream which contains the orbital information. But every 2 minutes on the even minute, it emits a time tick which can be recognized as the appearance of a 400-cycle switching tone. By measuring the time of arrival of that time tick every 2 minutes, you may get five, six, and sometimes seven of these points in any one pass, you can plot a "best fit" parabola. The point of the closest approach, of course, is the minimum point on the parabola and your time of arrival of the time tick is delayed by the propagation delay from the satellite to you. Again, the problem is how to determine that propagation delay. There are two ways: (1) by using the orbital elements, which are published regularly in the notices to mariners issued by the U.S. Navy Oceanographic Office; it gives information

*Director, Time Service Division, U.S. Naval Observatory, Washington, D.C. 20390 (202) 254-4546.

better than about 100 μsecs; and (2) by using the satellite signal directly to determine the range. This has been pointed out by Mr. W. Judge from Magnavox. It simply consists of using both the doppler rate at that point of approach and the range. Instead of measuring doppler which would make it more complicated, simply look at the curvature of the parabola which is nothing more than the rate of range change. You can envision that given a circular orbit with known radius, this is a function of the actual distance of the point of closest approach. The farther away the satellite is, the less the curvature of this point will be.

There is a simple mathematical relationship which has been worked out. The point is that here you have a system which offers timing down to (at the present time with our present system) about 10-μsecs precision, and to my knowledge no one in the U.S. is using it. Twice daily the satellite passes over practically every point of the surface of the earth. As I understand from the presentation of Mr. Rueger, there are certain improvements which have been envisioned that will make that time distribution even more precise and will significantly reduce the present data noise of about 10 μsecs. The receiver which we have at the Observatory is of the type which you saw in the photograph shown by Mr. Rueger, and it by no means reflects the latest state-of the art. I am sure many more advanced designs are possible.

In respect to TIMATION, you can see we are on the verge of using an experimental satellite for actual operational transfer of time. One single R&D type satellite can satisfy, as we believe, all PTTI global requirements anywhere with a precision which far exceeds what is required today. The problem is, however, that we cannot presently encourage development of receivers to receive the satellite signal, because it is only an experimental program, and we are not assured that there will be any replacement compatible with existing receivers.

MOON-BOUNCE TIME SYNCHRONIZATION

by Dr. Walter H. Higa*
and
Samuel C. Ward**

This report contains a brief discussion of the time synchronization experiment performed during the summer of 1970 with the Moon-Bounce Time Synchronization (MBTS) technique.

Within the last decade, the Jet Propulsion Laboratory became involved, first, with the RANGER series of spacecraft, which cruised near the moon and took pictures as they approached, and, later, with the SURVEYOR spacecraft series, which were landed on the moon. Several kinds of detailed lunar maps were made for the RANGER and SURVEYOR series; numerous radar studies using an X-band radar were required.

When a spacecraft merely cruises in space, a good stable oscillator is necessary to ensure doppler quality, but there is no real requirement on timing. The spacecraft in cruise mode has very little information to send, so the computers can be used to double-check and calculate the trajectory without having to resort to any exotic time synchronization between tracking stations. However, when the lunar orbiter series evolved several years ago, it required that the spacecraft be essentially stopped in space, which demanded very accurate navigation. The Jet Propulsion Laboratory was assigned the tracking duties for this series and was asked to provide an accuracy of 30 μsecs between tracking stations.

---

*Technical Staff, Telecommunications Division, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91103, (213) 354-4240.

**Mr. Ward was primarily responsible for data analysis.

The locations of the tracking stations--Spain, California, Australia, and South Africa--made it very difficult to utilize the LORAN-C technique; the possibility of utilizing the skywave at some of these remote tracking stations is now being investigated.

As a result of the lunar orbiter requirements, the use of the lunar bounce radar method of synchronizing clocks at the tracking stations was proposed. This method is a bi-phase modulated X-band radar. The objective was to derive an operational system that required very few technical personnel at the remote tracking stations. In other words, an X-band signal is transmitted to the moon from the Goldstone, California tracking station, and the signal is modulated so that it can be used at other tracking stations to provide 20 μsecs of time synchronization. Thus, all the complicated computations of such a system are performed at the transmitting site, and the remote tracking stations have only a very simple receiving system. This system recognizes that the computer is needed to figure the doppler correction for the relative motion between the tracking stations and the moon. It also recognizes that any measurements made at the receiving site should be very, very simple. The receiver is reduced to its bare essentials; thus,

- The pseudo-noise (PN) modulated X-band transmission is frequency compensated for all the doppler shifts from station-moon-station.

- The unique PN code is advanced in time by the known propagation delay and then scans ±30 μsecs each minute in 1 μsec steps.

- The local oscillator at the receiver is bi-phase modulated by the same PN code as the transmitter and is synchronized to the station clock.

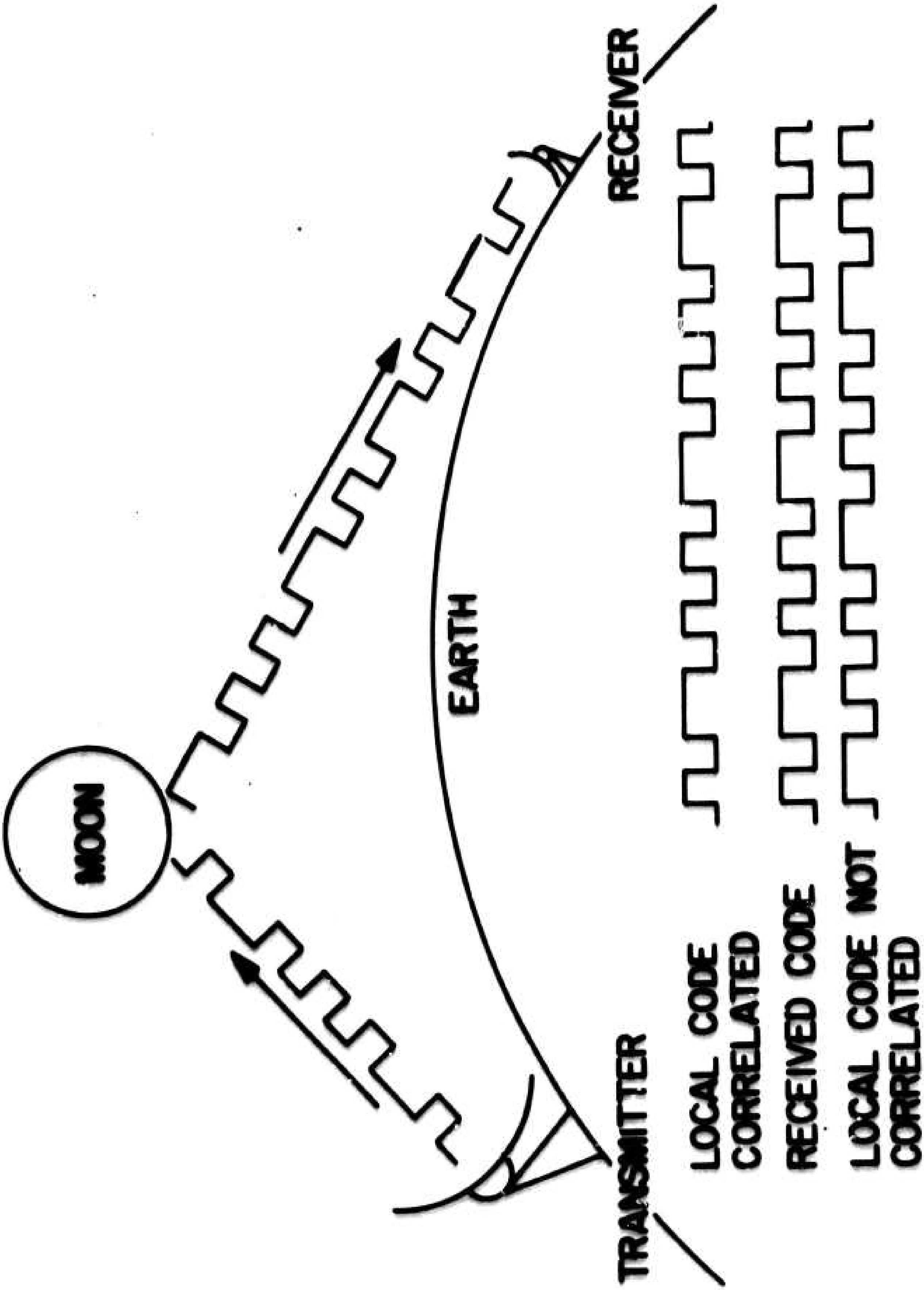
- The cross correlation of the received signal and locally generated code is recorded by a strip chart recorder to provide visual real-time measurement of the station clock error relative to the master clock at Goldstone.

The MBTS method was used successfully for $\pm$ 20-μsec clock synchronization between Deep Space Networks (DSN) stations during the Mariner '69 mission. Understandably, the originators of the concept of MBTS did not have the time to investigate the full capabilities of the method. The present experiment was undertaken to complete the investigation.

Figure 1 illustrates schematically how time is synchronized. In the X-band radar, a programmed transmitter takes care of the doppler shift and is so modulated with a unique pseudo-random noise code that the signal going up contains a modulation that is also generated by the receiver, and the two are, in effect, correlated between the received modulation and the locally generated one. The offset is then measured in terms of the correlation function.

If the transmitter signal were really advanced by the propagation delay and the local clock were indeed in synchronization with the transmitter site clock, the result would be both a perfect coherence and a strong signal output. Since the local clock is not expected to be in perfect synchronization with the transmitter clock, the code is advanced by the 2- or 3-sec propagation delay time and then retarded to 30 μsecs. For each second thereafter, the code is advanced 1 μsec until it is ahead of the propagation delay by 30 μsecs. Thus, if the local clock is within 30 μsecs of the transmitter clock, one should be able to observe it directly on a recording of the correlation function.

A typical trace on the strip chart recorder would show the two modulations coming into coincidence as maximum correlation was reached from a start of minimum or 0 correlation. If the correlation function were



DSN TIME SYNCHRONIZATION

FIGURE 1

the correlation of two square waves, it should actually be a triangular-shaped correlation response. But, because of tne time constant in a capacitor that is charging up, there is a gradual decay of the signal.

If there were no noise and if the moon were a very smooth sphere, one would get an idealized response; however, noise will be superimposed because the moon is indeed a very rough surface, and one finds that there is an effective subradar point--the point at which reflection occurs.

The subradar point does not remain stationary but due to liberation, it moves from hills to valleys within a 28-day period. The effective front cap thus consists of a complex surface, roughly 180 km in diameter, which moves from day to day. By tedious calculations, it is possible to compute the average deviation from sphericity of the varying subradar points. Figure 2 shows a graph of the varying altitudes of the effective front cap of the moon. Distance has been converted into equivalent propagation delay times for convenience.

Figure 3 shows the results of the MBTS experiment superimposed on the graph of Figure 2. The excellent correlation for May and June leaves little doubt that the lunar topography is the principal cause for fluctuations in the method. The month of July shows the same kind of correlation as for previous months, but a systematic error of approximately 10 secs was observed. These points are denoted by circled triangles. The exact causes for these systematic errors have not yet been determined, but either equipment failure or operator error, or both are suspected. The July experiments were carried out at a very low angle of elevation at either the transmitting site or the receiving site; this was the only operational factor that differed consistently from those of the preceding months.

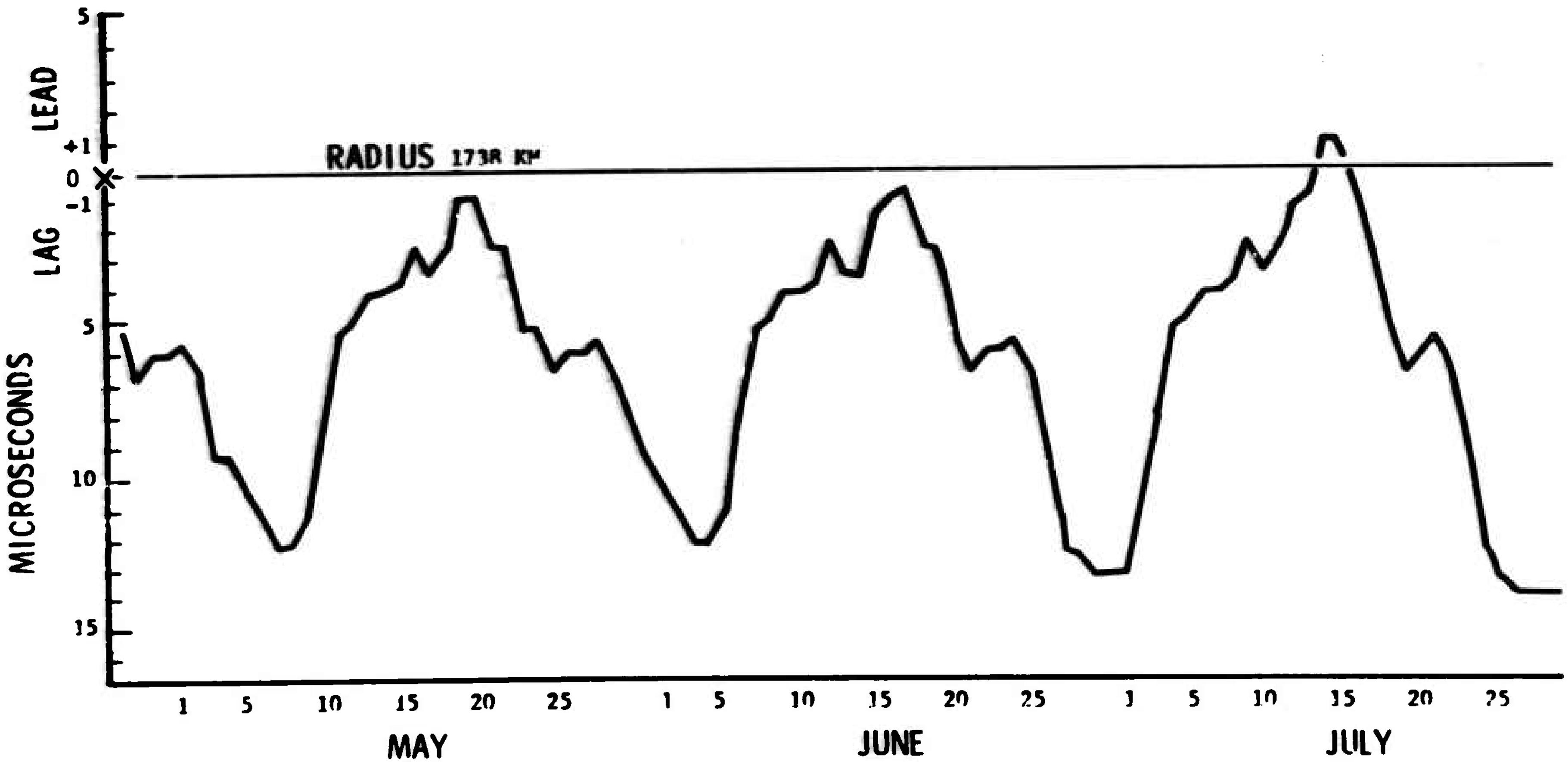
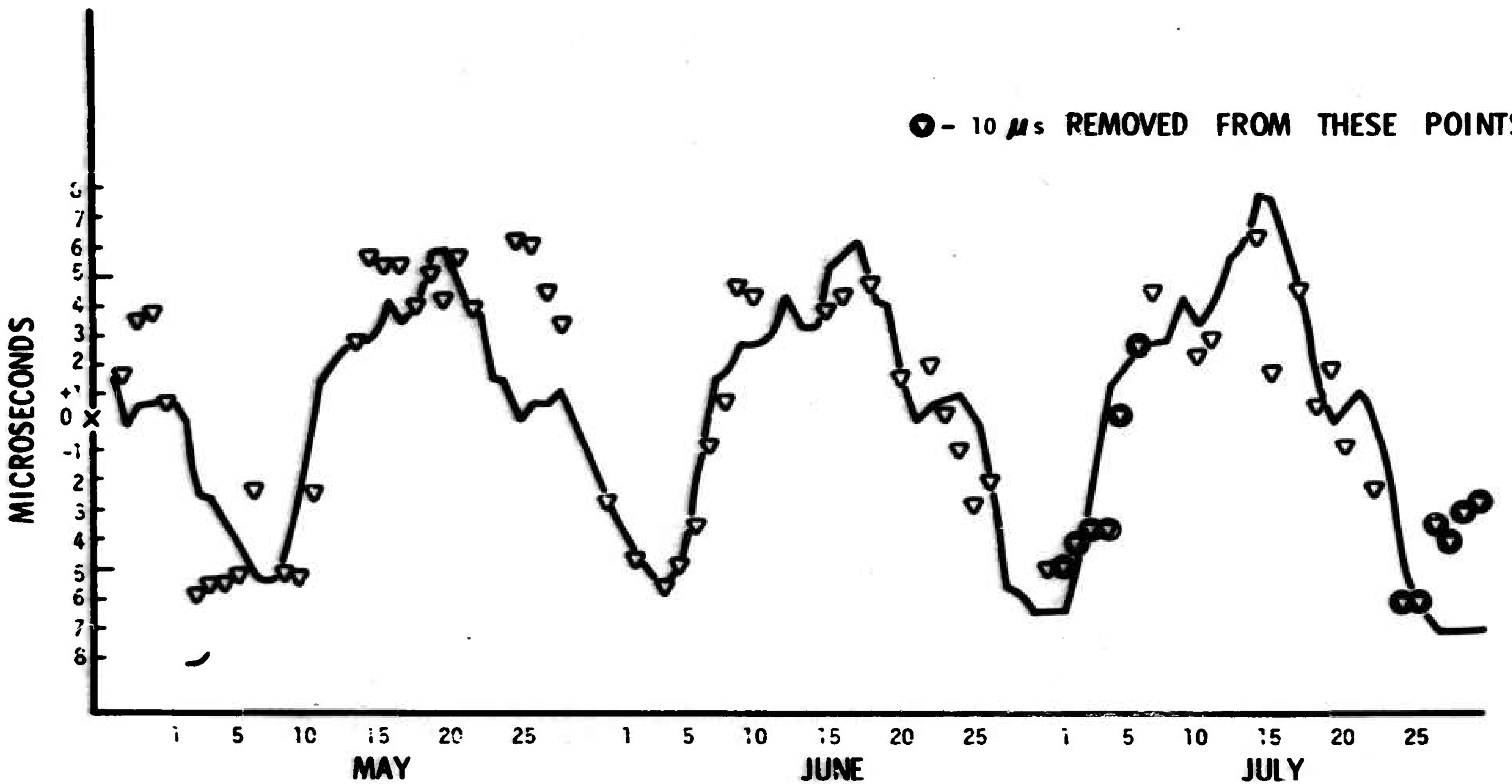

LEAD
LAG
MICROSECONDS
5
+1
0
-1
5
10
15
RADIUS 1738 KM
1
5
10
15
20
25
1
5
10
15
20
25
1
5
10
15
20
25
MAY
JUNE
JULY

FIGURE 2



USNO CLOCK 36 OFFSET FROM NBS CLOCK 8 AS MEASURED BY X BAND MOONBOUNCE SYSTEM

FIGURE 3

CONCLUSIONS

The precision of the MBTS scheme can be improved from around $\pm 10\ \mu$sec to around $\pm 3\ \mu$sec by correcting for lunar topography. The systematic errors must first be explained and removed.

Acknowledgement: The authors would like to thank F. Borncamp and R. Wells for assistance in coordinating the experiment. The help of NBS (Boulder) and the USNO is gratefully acknowledged.

TIME DISSEMINATION METHODS FOR NETWORK AND LOCAL TELEVISION - ABSTRACT

by George Kamas*

The National Bureau of Standards is conducting experiments in the utilization of television for the dissemination of time and frequency. The long-term objective of these experiments is to develop a television time dissemination system for the United States. Various techniques of television time dissemination and display are discussed. The paper will be available from the National Bureau of Standards Time and Frequency Division in Boulder, Colorado in the near future.

*Time and Frequency Division, National Bureau of Standards, Boulder, Colorado 80302, (303) 447-1000, Ext. 3378.

MICROWAVE, OPTICS, LASERS, AND OTHER EXOTIC SYSTEMS

by Robert Stone*

It is good to work in a real world if possible, and the real world in time and frequency has had a look over the years as shown in Figure 1. NRL has been active in this field since the early 1920's. The solid curve represents what the real need has been over the years in precision time and frequency, and the dotted curve represents the state-of-the-art. In the beginning years of electronics, time and frequency were thought of separately. Tuning forks, crystals, etc. were used to control frequency; pendulums and other similar devices were used to control time. For the greater part of the time, the state-of-the-art in time and frequency has been a factor of 10 greater in accuracy than was actually needed. Communication during this period was very simple and the time/frequency problems could be very easily met.

A major breakthrough in time/frequency techniques occurred with the advent of the ring crystal in 1930. By 1940, standards capable of maintaining frequency to 10^8 and time to 1 msc were available. During this period, operational requirements for precision time and frequency were also increasing. Navigation systems, such as LORAN, were coming into being and digital communication systems required in teletype systems were being introduced. In the 1940's, a number of 0 temperature coefficient crystals were being developed, such as the GT cut crystal in 1942 and the AG cut in 1950.

About 1960, frequency synthesizers were developed which allowed a much more precise control of transmission frequencies. Concurrent with

*Head, Radio Time and Frequency Section, Naval Research Laboratory, Washington, D.C. (202) 767-3454.

TIMING - NEED VERSUS TECHNOLOGY

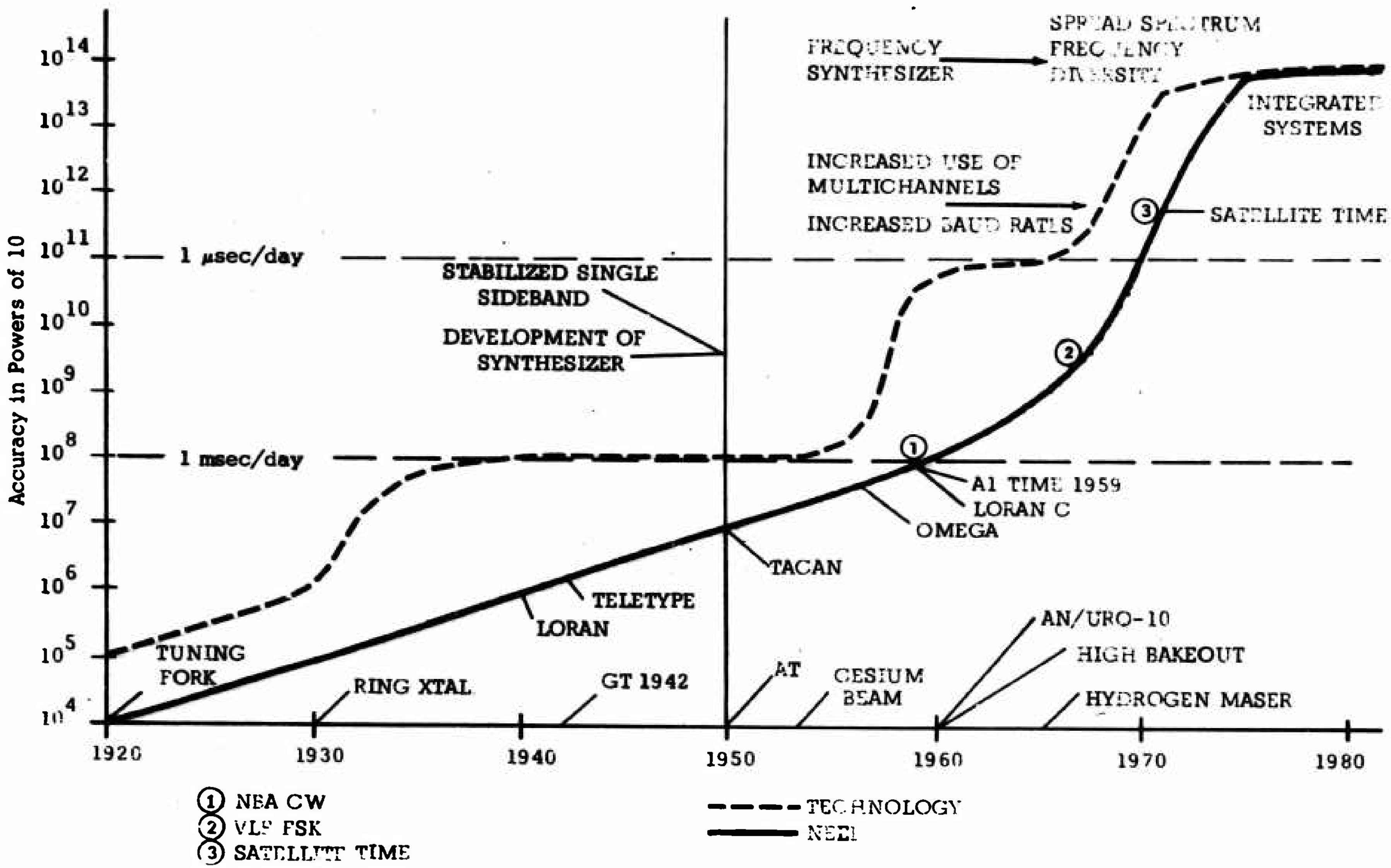


FIGURE 1

this was the development of stabilized single-side band systems. Prior to this point in history, the techniques which were used were simple and easily understood. Operation and maintenance were performed through intuition. All that was needed of precision time and frequency was sufficient frequency control to hold the signal within the band passes of the system employed.

About 1950, things began to change. More and more precision was being required in frequency and time. The intuitive approach to electronic operation and maintenance began to give way to a greater use of instrumentation. As more systems were developed (s s TACAN, OMEGA, LORAN-C in the navigation area; and use increased of the teletype, stabilized single-side band, higher baud rates, and the use of multichannel operation in the communications area), the demand for more precision in time and frequency increased. Figure 1 shows an increase of about an order of 10 in precision for each decade up to about 1950. Somewhere between the 1950's and 1960's, there was an upswing, until in the decade between 1960 and 1970 there was an increase of about three orders in the operational need of precision time and frequency. This need is still increasing. With the advent of satellite communication, spread spectrum frequency diversity, and integrated systems, it can be expected that eventually a time will come in which all the precision time and frequency which can be provided by thr e-art will be utilized in operational systems. If the present rate of increase continues, this point may be reached at some time in the next decade.

The aim of the time and frequency program at NRL is to provide a practical path by which users of precision time and frequency can refer to a common worldwide standard at the Naval Observatory. A hierarchy is envisioned, such as is shown in Figure 2, in which the standards are maintained at the Naval Observatory; a long-range means of transfer is provided to various parts of the world; then, branching from these points,

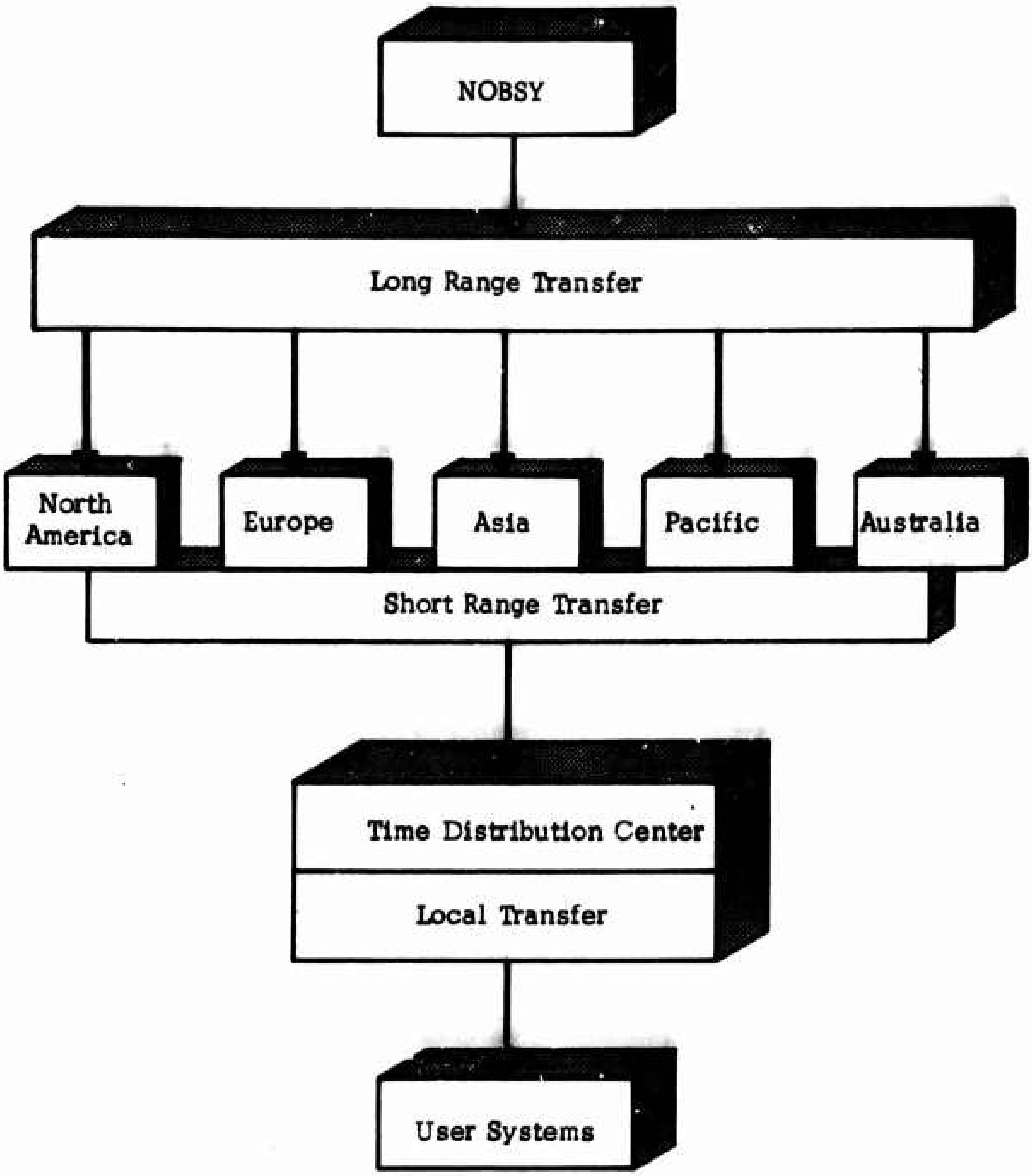

NOBSY
Long Range Transfer
North America
Europe
Asia
Pacific
Australia
Short Range Transfer
Time Distribution Center
Local Transfer
User Systems

FIGURE 2

there is a short range means of transfer to local time distribution centers which serve the user systems. This concept is shown another way in Figure 3. Any system which utilizes precision time or time interval also has a capability for the dissemination of time and time interval to the accuracy required in the system. The most economical way to transfer or disseminate time and frequency is to utilize those systems which require it. Such a system for long range transfer of time is the DSCS satellite system. Utilization of this system on a non-interfering basis will permit the transfer of precision time to about 1/10 msec anywhere in the world, which has the proper facilities. Following the same concept, short range and distribution of time and frequency would utilize available communication and navigation systems.

At present, the worldwide dissemination of precision time, as envisioned by NRL, appears as shown on Figure 4. Time will be introduced into the DSCS satellite system via a microwave link from the Naval Observatory. This link at present goes from the Observatory to NRL and Waldorf, but when the system becomes operational the link will go from the Naval Observatory to Brandywine, Maryland. Once in the DSCS satellite system, the transfer of time can be accomplished to virtually all major areas of the world. From these points, it is expected that other systems, such as LORAN-C, OMEGA, VLF, HF, etc., will be synchronized. Plans are being made to extend this hierarchy to the shipyard, the calibration center, and to ship and shore stations. One of the major problems in developing this hierarchy is to determine the users who should receive precision time and to set a system of priorities.

Short range transfer of time will be accomplished by cable, optical link, or microwave link. It is expected that the most extensive method will be the microwave link. Such a link has been established between the Naval Observatory and NRL. Figure 5 shows the characteristics of this link. The hydrogen masers at NRL can quite effectively be compared

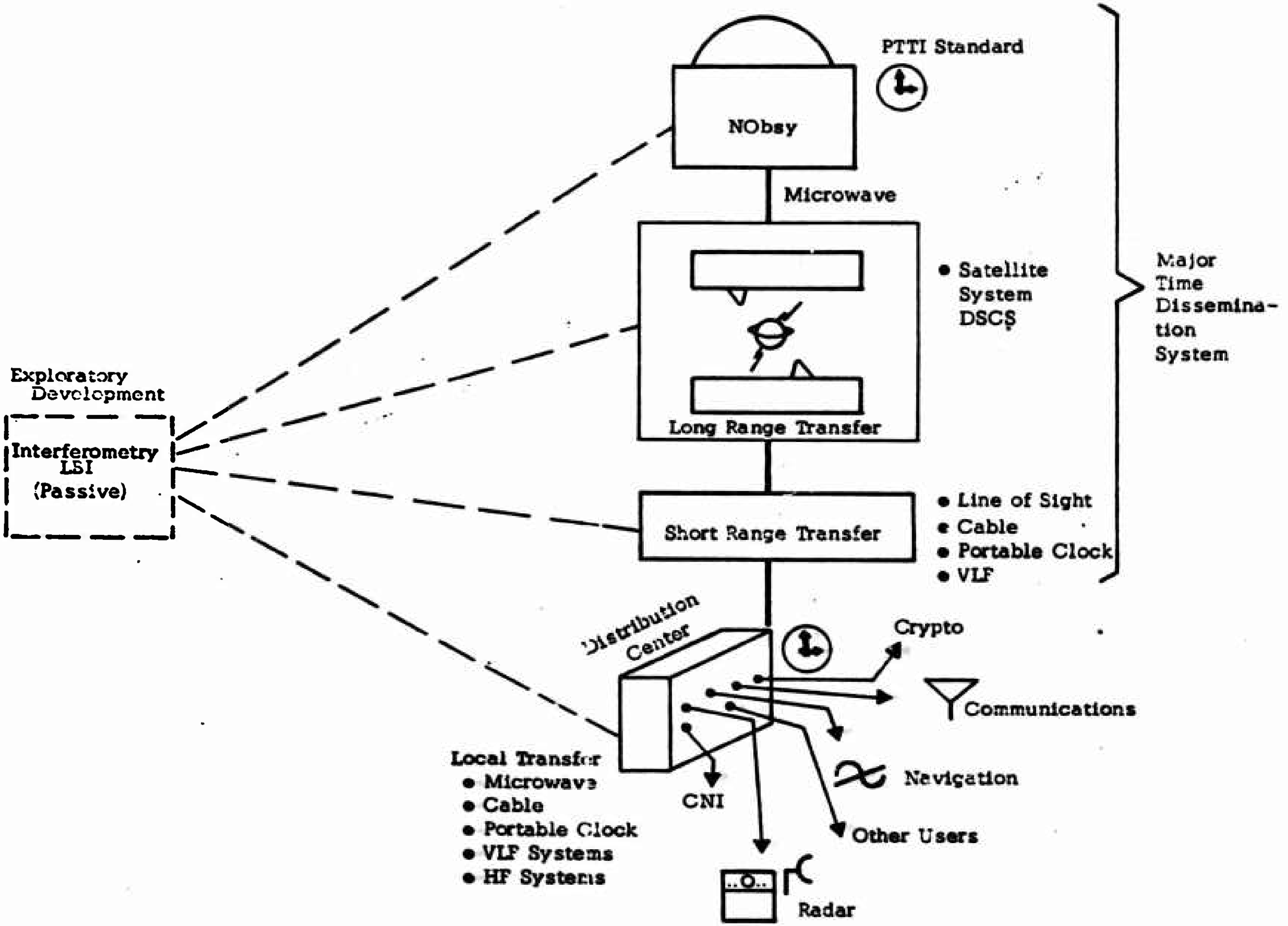

PTTI Standard
NObsy
Microwave
Satellite System DSCS
Long Range Transfer
Major Time Dissemination System
Short Range Transfer
Line of Sight
Cable
Portable Clock
VLF
Distribution Center
Crypto
Communications
Navigation
Other Users
CNI
Radar
Local Transfer
Microwave
Cable
Portable Clock
VLF Systems
HF Systems
Exploratory Development
Interferometry
LSI
(Passive)

FIGURE 3

FREQUENCY TIME/TRANSFER
1 x 10/11 .1 microsec.

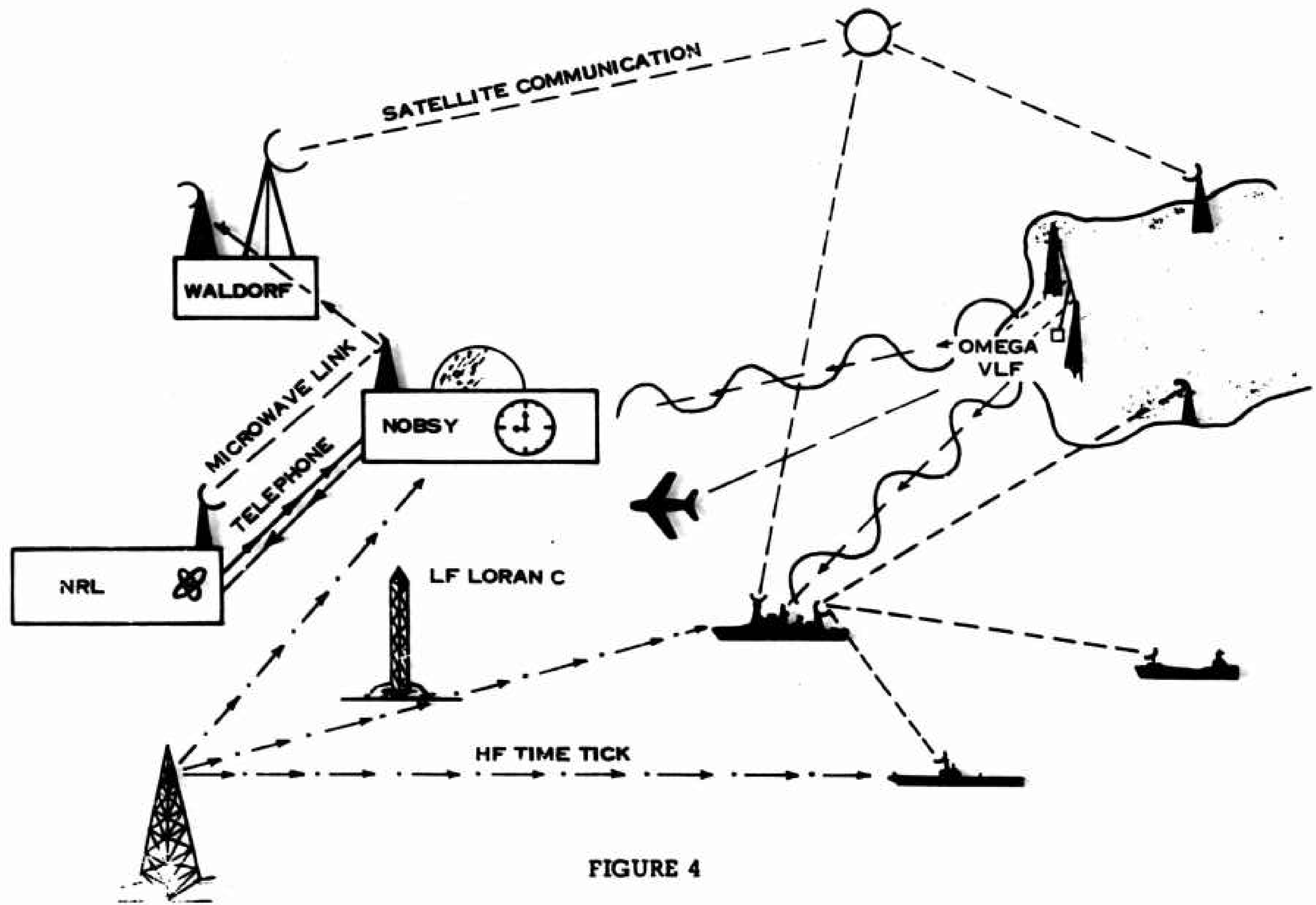
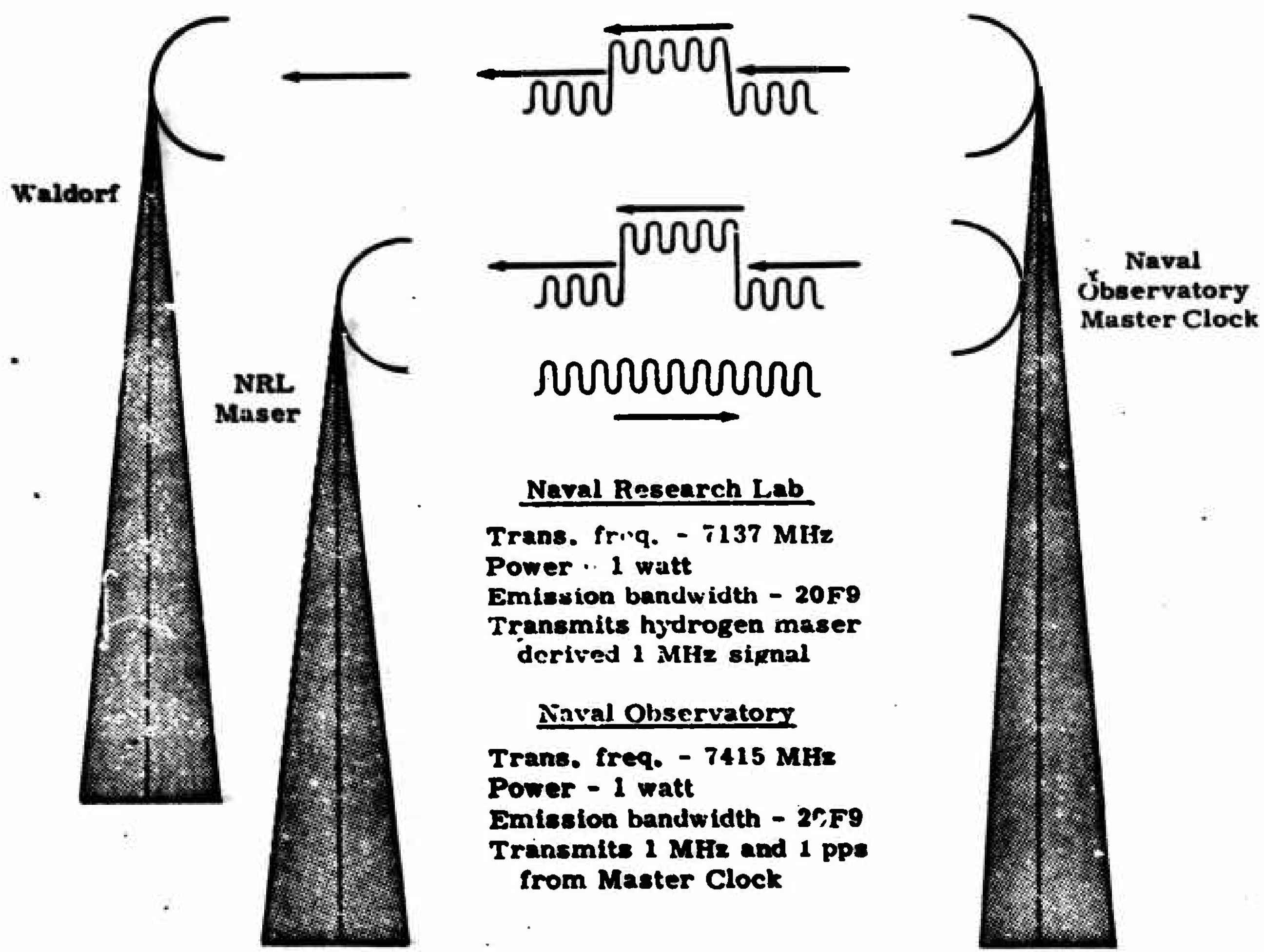


FIGURE 4

MICROWAVE LINK



Equipment: Raytheon Television Microwave Relay Model KTR-1000G

FIGURE 5

with the standards at the Naval Observatory via this link. Both a time tick and a 1-mc signal are transmitted. Accuracies of 10 msecs can easily be obtained. Although this link is devoted exclusively to the use of time frequency transfer, it is expected that comparable results will be obtained when the time transfer techniques are added to operational systems.

At present, NRL is investigating various operational systems which can be utilized for the short range transfer of time and it plans to develop techniques to extend the time hierarchy through these systems to the various DOD users.

PRESENTATIONS BY

Dr. G. M. R. Winkler

REQUIREMENTS AND PERFORMANCE FOR TODAY'S ATOMIC STANDARDS

by Dr. G. M. R. Winkler*

This paper addresses the requirements, specifications, and performance for atomic frequency standards in general. Requirements for universal time and certain general concepts of time-dissemination systems will be considered in later reports.

USER REQUIREMENTS

The first user requirement is the 100 msecs needed for celestial navigation. This contains a margin of safety, because most navigators are satisfied to know time to about 1 second. However, certain automatic systems under development or in use do need 100 msecs. From the total number of ephemerides, nautical tables, and almanacs used every year throughout the world, the total number of English-speaking users is estimated to be 100,000. It appears that their requirement of 100 msecs will not disappear in the near future. It has been pointed out that, once electronic navigation systems receive more widespread usage, the requirements may be relaxed; however, such relaxation is not expected within DOD; on the contrary, a need for immediate timing to 10 msecs (UT) has been indicated for some areas.

A more exacting requirement of 1 msec after the fact exists for universal time (UT_1) for geodetic purposes. Of course, this exceeds the state-of-the-art. It can be gotten only after about one or two months. The published International Bureau de l'Heure (BIH) values are precise to about 1 msec. (These are averages of about 50 observatories.) Anything more exacting

*Director, Time Service Division, U. S. Naval Observatory, Washington, D.C., (202) 254-4546.

than the precision value of 1 msec can refer only to synchronization requirements. But synchronization requirements evidently can be satisfied at the same time or with the same systems, which also give this UT timing information. If the two are separated and only clock time is discussed, then the simultaneous existence of several timing systems is admitted--a most uneconomical and undesirable situation.

A stated requirement of 5 μsecs worldwide exists for the Air Force calibration system. Many purposes, related in one way or another to space tracking, have a less exacting requirement of about 100 μsecs. The observation and tracking of objects in space requires clock time synchronization to about that magnitude. However, a margin of safety is always desired, which explains many requirements that go down to a 10-μsec range or less.

A fourth area of requirement has been generated by the recent evolution of the time/frequency (T/F) technology, or time-ordered systems. This technology presents two general requirements. Systems that require the simultaneous emission of many, many signals on the same frequency need a very exacting ordering or assignment of time slots. This system is known as the time frequency collision-avoidance system proposal. Other requirements, then, come from the need to measure location to a very high degree of accuracy by measuring the times of arrivals of signals emitted from navigation transmitters. A range of 100 to 500 nsec is listed as a primary concern. This requirement covers most, if not all, of the systems currently being studied, under development, or in R&D. Some 100 users require that degree of precision at present. If, however, any of these systems is implemented during the next years, the number may easily increase to thousands. Some requirements have also been tentatively listed on the order of 10 nsecs for limited areas.

When the list of requirements for new distribution systems or high-precision clock performances is considered, it appears that 100-μsec

or 200-μsec precision figures would leave a very large number of users unsatisfied. Therefore, effort should be concentrated on systems that have the capability of satisfying any of these requirements, i.e., systems that can give $\frac{1}{2}$ μsec or better.

SPECIFICATIONS

After this very short overview of existing synchronization requirements, the specifications for clocks or frequency standards to be used in these systems are discussed in the following paragraphs. There is, of course, a choice: (1) a continuously available synchronization can be assumed (e.g., the system described by Mr. Stone or any system that has continuous two-way communication, such systems are not considered to be typical time-frequency systems); or (2) systems that for months would require a maintenance of synchronization to microsecond precision, without any access to synchronization. In the first case, sophisticated oscillators would not be required, thus very cheap crystal oscillators could be used. But the tools required to maintain resynchronization reliability under all circumstances in the presence of noise, jamming, and spoofing would consume all your resources.

In the second alternative a significant advantage would be gained by being able to live for extended periods of time without any communication link; on the other hand, the selection of a clock that would offer precision, uniformity of operation, and the utmost reliability would prove a problem. It is somewhere between these two extremes that one has to select one's approach. In a comparison of the cost effectiveness of precision clocks, certain numbers were assigned to the initial cost, service requirements, stability and performance, and reliability of the clock; to production experience, and to sensitivity to environmental conditions, magnetic fields, altitude, high pressure, etc., and a simple formula was derived. In this comparison the quartz crystal oscillator came out far

ahead of every other approach, not surprisingly, because the technology has been fully developed over the last 40 years. On the other hand, the most glamorized frequency standard--the hydrogen maser--did not look as good. (Such comparisons are useful only if one has all the freedom to develop a system. More often, the engineer must accept requirements blindly, is given no opportunity to point out certain pay-off possibilities, and has no choice but to look at what is available.)

At the present time, the Navy Electronic Systems Command is working on a specification for cesium-beam frequency standards, which is an extremely difficult task. On one hand, the largest number of requirements, including requirements projected for five years hence, must be satisfied. On the other hand, one cannot be exclusive. A good specification ideally would also encourage competition among capable contractors but exclude those with mediocre or poor performance records. But what kind of performance can one expect?

PERFORMANCE

As an example, the performances of cesium beam standards observed at the Naval Observatory are reviewed in the following paragraphs.

Before a portable clock is sent on its way, a frequency adjustment is made at least one or two weeks before departure to ensure that the clock's rate is as small as possible with respect to the Observatory Reference (see Figure 1). When the clock leaves, a time measurement is performed. When it comes back the same time difference should be expected, but, in effect, a small "closure error" is observed (Δt)--a sign convention that $+\Delta t$ means the clock has lost time. The most likely closure error of course will be zero. There is an equal probability for closure errors to be plus or minus if, for a moment, certain very small, predictable relativity effects are ignored. However, these are still not

PORTABLE CLOCKS

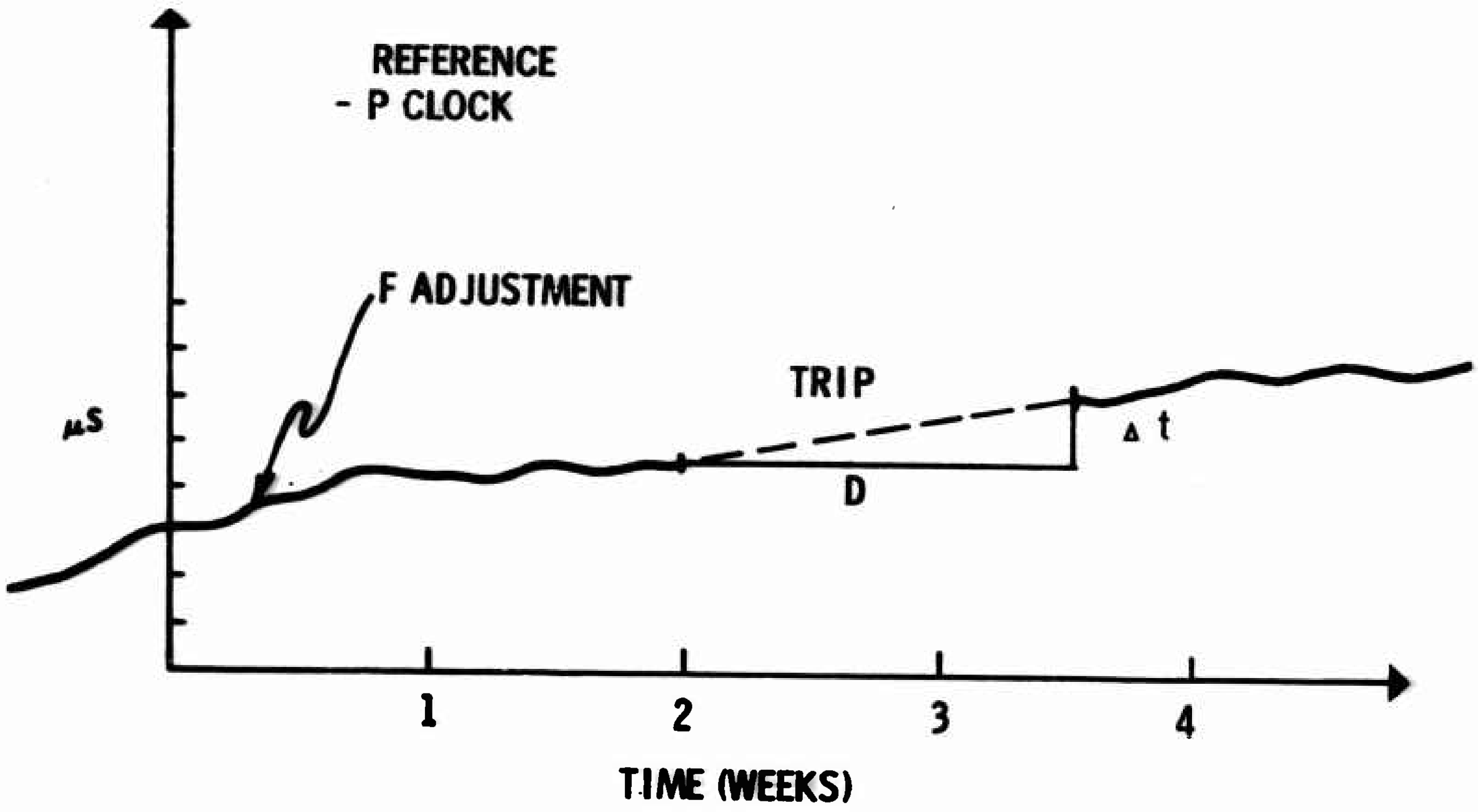


FIGURE 1

significant, so it is expected, on the average, to have a closure error of zero, and the performance of the clocks will be stated in the half bandwidth, so to speak, of that distribution.

Figure 2 shows two samples of actual measured performance. To arrive at these figures, for example, assume 27 trips for one time interval, and 26 trips for a second time interval. Of those, only the longer trips in excess of two and one-quarter days have been considered. The sample size is the same as well as the mean duration and the sigma duration. The average closure error is +0.1 μsec in the first case, and -0.5 μsec in the second sample. However, these numbers are not too meaningful, because of the sigma of about 1 or 1-1/2 μsecs. Figure 2 also lists the average of the absolute closure error, $|\Delta t|$ and the rms Δt; +2.4 μsec is the largest closure error in the first sample and -3.9 μsec is the largest closure error in the second sample. In addition, the first sample contained only 5060's and the second 5061's. The second sample has a somewhat poorer performance, which could be caused by a number of difficulties which was experienced with the 5061's shortly after they were introduced into the system. One component--the integration capacitor--caused us some problems initially; however, these numbers would not reflect a significant difference in the two standards on trips.

The question is how can one explain such a performance if one looks at performance measures taken in a laboratory.

Clocks are routinely measured at the Observatory in reference to the Observatory's average time scale. Such a clock average gives an extreme degree of redundancy and reliability of operation. The time scale which is used as reference is the average Observatory time scale.

If times for individual clocks and their frequency variations are plotted (see Figure 3), the variance is taken as was initially introduced by Dave Allan in the special issue of Proceedings of the IEEE, February 1967.

PERFORMANCE OF USNO PORTABLE CLOCKS

ALL TRIPS WITH D > 2-1/4 DAYS

PERIOD	NUMBER OF TRIPS	D MEAN DURATION	$\overline{\Delta t}$ + LOST	$\lvert\overline{\Delta t}\rvert$	rms Δt	LARGEST $\lvert\Delta t\rvert$	COMMENT
MAY 66 - FEB 68	27	15.5 d ±8	+0.1 μ ±1.1 μs	0.82 μs	1.1 μs	+ 2.4	HP ALL 5060's
APR 69 - JULY 70	26	14.1 d ±8	-0.5 ±1.5	1.15 ±1	1.55	-3.9	HP ALL 5061's

FIGURE 2

The variance is used as the standard notation and the frequency variations are essentially plotted as a function of integration time: 0.1 day, 1 day, 10 days, and 100 days. The individual cesium clocks fall into a general branch with a slope of minus one-half. That slope is exactly what one would expect if the variations in the disturbances are strictly random. It is the same law which governs any random statistical process, that over a larger number of samples the variations decrease as one over the square root of the number. And the same law, of course, can be expected here. It is remarkable that the clocks, which were selected as better-than-average performers out of a total sample of about 60, fall into a band which goes at that slope of about $\sigma(2, \text{tau}) = \dfrac{2 \times 10^{-13}}{\sqrt{\text{tau}_{\text{days}}}}$. The difference in quality between clocks is, however, noted by the point at which performance deviates from the heavy solid line and branches off horizontally. A relatively poor clock like #105B branches off at a point with an averaging time of less than one day. A very excellent clock, like #279, branches off at an averaging time of ten days; there is one best performer with a one-sigma frequency variation of three parts in 10^{14} for an averaging time of 40 days. It must be emphasized, however, that all of the performances shown in Figure 3 have been obtained under laboratory conditions. Clocks are separated in space, and they are individually operated, on individual power supplies, to assure that all variations are as random as possible.

Why do clocks branch off at various integration times? The major reason is that for such long intervals, the probability becomes so high that systematic, irreversible frequency changes occur. In a cesium beam, such an irreversible frequency change for instance, would be caused by a change in the control voltage of the Zener reference diode which controls the C-magnetic field. Or, furthermore, a systematic change can occur in the magnetic properties inside the transition region. Any one of a possible

$\delta \frac{\Delta f}{f}(2,\tau)$ PLOTS FOR VARIOUS CESIUM BEAM CLOCKS

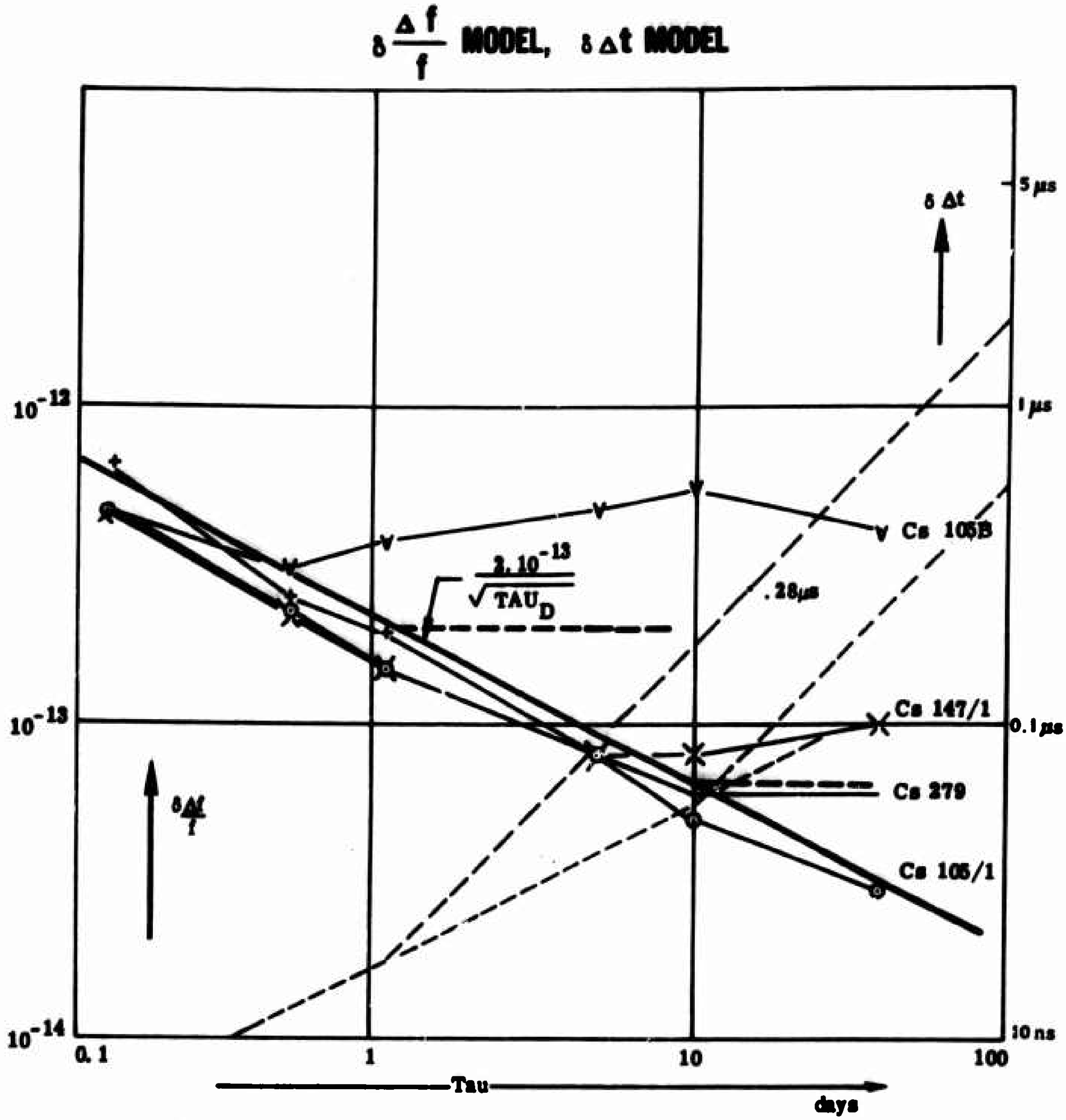


FIGURE 3

10 or 15 critical parameters which influence the frequency stability are subject to systematic change eventually. The longer a clock is observed, the greater the probability that such systematic changes start to predominate, and they will cause an upward swing to a "random walk" frequency modulation performance. For planning purposes, a typical performance has been assumed; this is shown as the heavy solid line in Figure 3. For the best available cesium clocks, that formula has been used as a model. One has to use two branches: one for the random frequency noise behavior (white FM), and the second to state the point at which the clock will "branch off." Variations in frequency can also be expressed in variations of time. Time deviations (dashed line) are then represented by a straight line with slope +1/2 as long as the model (heavy solid line) follows down the slope -1/2 and then will branch off at a slope of +1 from the point where the systematic distrubances begin to predominate. Now, assume that a selected portable clock, if left completely undisturbed, would perform as well as one of our best clocks. Suppose that clock is exposed to the troubles of a journey or moved around; suppose it is turned around in the earth's magnetic field; or exposed to vibration, or to shock. Suppose it is moved in an airplane to make a trip; it is moved into another laboratory; it is left there for one day. Suppose all of these things and then it may be reasonable to assume that something is done to this clock which can affect its systematic behavior on the average of about once a day. A performance along this model for a trip of 14 days is expected with a variation in time of roughly 0.3 μsecs. The actual performance is about three times poorer, but it is very much in the same ballpark. Therefore, similar considerations can be applied to many timing applications.

If less exacting requirements are stipulated so that a time base is necessary without any recourse to external synchronization for periods no longer than one day, then one can be satisfied with a standard which

will branch off or go up into the random walk at that time interval as a rubidium standard does. A rubidium standard has a better performance, in general, up to about one day, than a cesium clock; however, it deteriorates in its performance rather soon.

There are a few hydrogen masers which we have seen or which we use repeatedly: two at the Naval Research Laboratory, which are accessible to us via the microwave link, and one at the Observatory which is available directly within our Laboratory. The performance of these hydrogen masers for short periods of time (such as fractions of a day) is absolutely outstanding; they are unquestionably, the best clocks in existence. When integration times of ten days or longer are reviewed, they become disappointing, because they tend to be poorer than the best cesium standards and, of course, poorer than the average of all cesium standards. Consequently, the best use of the hydrogen maser seems to remain in applications which require the utmost in spectrum purity or the utmost in suppression of phase noise for integration times shorter than a few days.

For many applications, engineers who have an understandable urge for a sufficient margin of safety and available precision, tend to select a high precision standard. If there is any question, they select the better, or what they feel is a better standard. This can be a very dangerous tendency. For instance, assume it is necessary to have a frequency stability for a timing requirement of a fraction of a microsecond for a couple of days. That would be a requirement typical for navigation-timing applications, or for systems such as OMEGA or LORAN-C. Further, assume that one would follow this tendency and specify something more elaborate than a commercial cesium beam standard. It would be a great mistake, because the available measurement precision also enters. If phase differences cannot be measured with a precision greater than about one-tenth of a microsecond, then it takes a very long time to make full

use of even a cesium standard. It is this phase noise which places an ultimate limitation on the usefulness of a precision frequency standard. It appears, therefore, that future requirements will not go towards an increase in short-term stability over what has been accomplished with hydrogen masers, but instead will go towards a more reliable exclusion of systematic changes in frequency standards for longer periods of time because of these benefits for T/F systems use. Clocks can be left alone for longer periods of time and that means clocks can be selected which perform better in this area.

DISCUSSION

Dr. Reder

What is currently being done to improve cesium standards; does anyone have a contract?

Dr. Winkler

Does anyone want to express himself directly on this question? No response to the question. What is being done to improve cesium standards at the moment? Apparently "no response" indicates only an absense of Government sponsored R&D. We know that there is continuing commercial development.

Cdr. Potts

I would like to take a couple of minutes to explain our experience with the commercial standards we have. We own all Hewlett-Packard standards--a couple of 5060's, and mostly 5061's on the order of 80 cesium standards so, for the last year and one-half, we have undertaken complete maintenance of these standards. We ran into some problems on the commercial standards. Initially they were quality controlled. There were some bugs which were not removed, such as the integrator capacitor. There have been some failures which have occurred several times, and it has been a learning curve for us as well as for Hewlett-Packard. I prefer not to single them out, but they happen to be the only successful manufacturer of cesium standards and they are the only standards we have. We have had a direct link back to them in an effort to improve succeeding models of cesium standards. It has been a continuing program with us to document all problems and to inform Hewlett-Packard of them then, in turn when we receive standards from them, check to see if those problems still remain. I would solicit a comment from Lt. Dave Clements of our

Laboratory, who runs the time frequency laboratory and our cesium maintenance, and perhaps he can give you a little better idea of the real numbers.

Lt. Clements

We have shown recently, in the last eight or ten months, a mean-time-between-failure of all the units pushing 20,000 hours for the cesium standards, and the cooperation we got from Hewlett-Packard has been quite good. They have done some design changes within the unit on their most recent models concerning their operational amplifier, and they have also done some work on their synthesizer assembler. Recently, we received a batch of new units and we ran into a quality control problem inasmuch as 11 of the 23 units we received had something wrong with them. So, other than the quality control, the design work on the cesium seems to be gradually improving.

Dr. Winkler

I would like to make a further comment here. Mr. Acrivos at the Naval Observatory has organized very crucial and difficult environmental tests. Such tests have also been performed by Dr. Hafner in Ft. Monmouth. A recent report summarizing the results of Dr. Hafner's tests was issued by Sperry Gyroscope and is available upon request. One of the results of these tests, and one that has been overlooked in our testing up to now, is the very great sensitivity of these standards to AC magnetic fields. Some standards reacted extremely poor to an exposure. Both companies which produce cesiums, are making special efforts to improve and to reduce the the sensitivity to the AC fields. The sensitivity is not all centered in the beam tube alone; it is also in the synthesizer and frequency multiplier, where problems apparently exist.

Mr. Acrivos (USNO):

Hewlett-Packard is making modifications, both in their tube and in their magnetic shielding by installing new metal shielding around their synthesizer and multipliers. The first unit will be delivered for testing under NAVELEX sponsorship on December 15, 1970, and I believe, when you order the tubes from now on, the new tubes will all be equipped with additional shielding.

Dr. Winkler:

There is a second development which I would like to mention. Probably many of you have become aware of the nine-inch beam tube and the small portable standard or small airborne cesium beam standard engineering model which was shown by Hewlett-Packard. There is, at the present time, no intent so far as I understand on the part of the Hewlett-Packard company to offer that engineering model as a production unit. However, we have explored it, and there is a willingness on the part of the company, if a sufficient number of units should be ordered, to start a hand-made production series. The estimate which we have received has been $35,000 for the first unit. If we order more, presumably that price would go down. It appears that the performance to be expected from a very small cesium standard of this size would be still much better than rubidium standards that are available up to now. It could be carried in an airplane under the seat. It would have power for 10 hours, so it would not have to be connected to the aircraft's supply. There is a tentative specification for that instrument here, and it is available for anyone who has not seen it yet. It is certainly a most desirable unit to try out, and I wonder whether many agencies, even outside DOD, would be interested in such a unit, and whether or not we should pool our resources into one order for a number of these. The Observatory is interested in ordering one.

Beck (NRL):

Is there any thought on the physical size constraints of the device? There is a new device coming out with a long depth, and I think that there might be better physical constraints.

Dr. Winkler:

Yes, let me read the size quoted: 4-7/8" x 7-5/8" x 19-9/16", 40 pounds weight, 28 watts, DC 22 to 35 volts or 115 volts, 50 to 400 cycle. Its long-term stability is quoted to be better than one part in 10^{11}, and it includes any combination of environmental effects. It will withstand certain environmental conditions operating $-54^{\circ}C$ to $+71^{\circ}C$; storage $-62^{\circ}C$ to $+85^{\circ}C$; altitude 0 to 30,000 feet; vibration a quarter G 2000 Hz; shock MIL-E 5400 L, 30 G, 11 msecs; magnetic field 0 to 2 gauss. These are the specifications by Hewlett-Packard. So, my proposition is to invite an expression of interest to join in a procurement for a few units to be used in some of our portable operations and I am sure that would drastically reduce the cost of portable operations for everyone.

Mr. Chi:

If I may make one more remark on this, we heard previously some really hair-raising requirements or would-be requirements, and I think that the time is now to invest some money in improving these clocks. Because if you wait too long, then you have to start all over again, and it will cost dearly.

Dr. Winkler:

Thank you for your comment. I think the existence of a number of competitors will inevitably bring down the price and improve the performance. The existence of one competitor who very vigorously entered the market has already accomplished something in that respect.

Mr. Chi:

The specification for the new Hewlett-Packard short-beam tube is designed for general-purpose type, and that is why it takes 40 watts. I wonder if you want to follow the company specifications to develop such a unit, since there is very little difference in terms of power requirements. The advantage of that unit is that it is small, and it should also consume less power (which the beam tube indeed does, it consumes much less power). There is no reason to add on to it so much electronics, which may not be neccessary for the intended use.

Dr. Winkler:

It is my understanding that the electronics proposed are a bare minimum requirement and even the one pulse-per-second output would not be available except as option. There would be no clock movement; you would just have the one pulse-per-second output and get your seconds and minutes from good old WWV.

Mr. Chi:

Well, I understand that the beam tube takes less than 10 watts total power. So with the technology of electronics and possibly a simpler power supply where most power is wasted, one probably can reduce the power by a factor of two.

Dr. Winkler:

But after all, there is only one way to find out, and that is to purchase a few of these units and test them. I think that this is perhaps a more economical approach for us than to start a separate R&D project.

Mr. Chi:

I think without making any commitment, if you paid the first $35,000, we will be willing to buy the second if they come down in price.

Dr. Winkler:

Yes, but I believe that price is available only if you buy all of them at once.

Mr. Lieberman (NAVELEX):

We glossed over rubidium, though, and I understand that many of these systems that are coming out are going over to rubidium. I wonder if you could discuss comparative differences between rubidium and cesium and your crystal oscillators.

Dr. Winkler:

Let me emphasize that in the Observatory we have not had nearly the same experience in respect to rubidium standards in comparison with cesiums. We have had some of them in the Observatory for extended periods of time, both the Tracor unit and the Hewlett-Packard unit. We have also received reports, particularly from Mr. Easton's group at NRL, who for some time made differential phase measurements against our signals. We have evaluated about five to seven. I would like to have Mr. Easton give us some additional comments. But to answer your question with regard to the rubidium standard in comparison to the cesium, I believe it is a fine standard-- the same performance you would expect from an extremely fine crystal standard. It holds its frequency during short-time stability for periods shorter than one day, better than cesium; but when it comes to longer periods, which may be of no interest to many systems, then you are forced to make continuous adjustments of the C-field or, if the adjustments become very large, change one digit in the synthesizer, in order to keep on the same specified system frequency. If you have continuous resynchronization capability in a system, and if you are willing to put up with that need to make adjustments, then the rubidium standard may be an excellent choice. On the other hand, if the system is designed properly from the

beginning, these adjustments will not be difficult because you can do it by way of adjustments inherent to the needs of the system. For instance, in LORAN-C, you could perhaps make adjustments by means of very small phase steps. Or, in the OMEGA system, as I understand it, there are regular phase adjustments performed to bring the rates of all standards to the same nominal value. You can incorporate the adjustments due to the drift of the rubidium into these adjustments which are already necessary. So it depends upon the system's configuration, I would say, to decide that question, and I completely agree with your thesis that one should not overlook it. It is a standard which is half as expensive and certainly about as complex, and presumably, it will have better lifetime characteristics of its primary frequency controlling elements than a beam tube, which is rather good already, in the case of cesium. One should not overlook the rubidium standard, I perfectly agree with that. I would like to ask for more comments.

Mr. Ed Rickey (Aerospace Guidance and Metrology Center):

I would like to comment on the rubidium standard. Just as you were saying, continuous synchronization is a must if you are going to consider instituting a rubidium standard. If you are going to be at a remote location where you have a requirement to maintain no worse than 500 msecs in six months for example, you are wasting your money to buy a rubidium, even though microseconds is not a very stringent requirement today. Nevertheless, you cannot guarantee yourself 500 msecs in six months if you have a rubidium with no resynchronization capabilities. As a consequence, I just want everyone who may be thinking of buying a rubidium standard to keep this in mind, and if they are not going to have the resynchronization capability where they are going to install the system, then it is a waste, completely.

Dr. Winkler:

The Coast Guard, I think is in an excellant position to comment on this question, would you, Cdr. Potts?

Cdr. Potts:

Yes, we have used the rubidium standards for a number of years. We do not have a large family of them, but one of the major problems we found in rubidium standards, no matter who makes them, is their reliability. I tend to live in the real world. We have a system, or systems, to operate. That means we have standards scattered all over the world. We must keep them operating-- not just one in a laboratory somewhere or in some nice environment, but, quite frankly, the rubidium standards have not cut the mustard! I would like to point out also that if you are considering a single standard, or even several, which are going to be within the range of some quality electromagnetic emission, you can purchase a good quality crystal phase-lock it to the received carrier from whatever source you want, and enjoy the best of two worlds from the good short-term stability of the crystal oscillator and the excellent long-term stability of the received carrier. So you can see that you do not need to spend a lot of money, if you have something available in the atmosphere.

Mr. Lieberman:

Along these same lines, and since I did mention that new systems are coming in which use the rubidium, do we now have any capability of calibrating them, as to their full capacity?

Dr. Winkler:

It appears to me that we have touched upon an issue where strong beliefs are at stake and we will cover these points later.

Mr. Chi:

I would like to discuss the rubidium gas cell. Number one is to put it in its proper perspective. As far as frequency stability is concerned, the short-term frequency stability is better than the cesium. However, when the long-term stability exceeds one day or so, it is a factor of almost 100 better than crystals, although it may be a factor of 10 poorer than cesium. Reliability of the rubidium gas cell has not been proven worse than that of cesium, although there might be some problems which we have been investigating for the last year or so by ourselves and with the Goddard Space Flight Center, and also we have given small support to Dr. Vanier at Laval University in Quebec, Canada. The problem involved in the rubidium gas cell is that there is long-term drift, the cause of which no one exactly knows. The most likely sources will be the exciter in the light source, the filter, and the absorption cell. The approach at the moment for instance is to solve the light intensity problem. One method is to use a gallium arsenide type of laser. Also, we have another approach which I will leave for future discussion. For the gas cell part, we are using a new material, namely ruby, and we try to evaporate ruby on the wall. Hopefully, that will tend to reduce the systematic frequency drift. However, I do not have any results to report, since this is not my work. This would generally indicate that there is a certain amount of effort in reducing the systematic drift. So, if you can stand, in my opinion that is, with the crystals for whatever operation you may be doing, then the gas cell probably would be at least a factor of 10 or 100 better than the crystal in the long-term drift. This means that you will not have to correct quite as much; the power consumption we should be able to bring down. This is one reason why, in the short cesium beam tube, if it is properly designed, there is no reason for the electronics and power supply to consume 30 watts of power. It should come down by at least a factor of 3 or so to 10 watts. These are some of the things which

I think we should look into very carefully. The next area of comment is the hydrogen maser. So far as the hydrogen maser experience is concerned from our measurement, the stability exceeding one day is a little bit better than what was indicated, although it may not be beyond ten days. If you recall, Harry Peters did show a curve that showed that he obtained the desired result.

Dr. Winkler:

I did not want to say that the hydrogen maser is "no good." As a matter of fact, this is the best clock anywhere for short integration time, even for the next five years, unless we have a major breakthrough in another principle. My comments were solely directed to the experience which we had using the Varian (manufactured later by Hewlett-Packard) design and modern electronics. But, as has been pointed out by Mr. Phillips (NRL), one part in 10^{13} is an excellent stability, and by no means anything to be sneezed at.

Dr. Reder:

We have had ten rubidium standards since 1965. Just to answer your question, Mr. Lieberman, out of this ten, only one holds the frequency to approximately 10 μsecs a month. The other nine standards have a bigger drift. This is point number one. Point number two is one which some people may overlook on the rubidium: you must reset the crystal from time to time because crystal drifting--despite the high servo-gain--would cause an appreciable frequency change over a period of six months. The last point I want to make is with respect to reliability. Rubidium standards were considered more reliable than cesium standards about five years ago: however, I doubt if that is still true. Because according to the ten we have, I would say that the reliability with respect to the rubidium gas cell and the excitation lamp, is probably about the same as that of the cesium beam tube.

Dr. Winkler:

These questions are of great importance. and I would very greatly appreciate receiving more information. In the meantime, Mr. Easton is here and I wonder if he has any comments to make on his experience concerning rubidium standards.

Mr. Easton:

I am afraid our experience has not been as great as testing eight or so. We only tested two, and those two did test out very well for integration times of one day, as compared to cesium standards.

Dr. Winkler:

It appears that we are approaching the end of questions or comments. Before I move to a different subject, let me mention that NBS has just published a Technical Note 394 by Dr. Barnes, Mr. Chi, Dr. Cutler, and others. It is actually a group that is working in support of efforts to come up with proposals for an IEEE standard for specifying frequency stability. According to my copy here, it is for sale by the Superintendent of Documents for 60¢, and you may get some of them free from the Bureau. It is NBS Technical Note 394, "Characterization of Frequency Stability."

Mr. Lieberman:

We are writing the specification for cesium. We are just in the process of the final draft, and I would like any comments you might have so that we can include them if there are any special parameters needed. We think we are trying to get a cesium standard to satisfy everybody, but at this time we do not know.

EXPLANATION AND REQUIREMENTS FOR UNIVERSAL TIME

by Dr. G.M.R. Winkler*

This subject strongly depends on feedback and is one of extreme importance for the Observatory, which asks for your patience, all of you who are not directly concerned with the subject, the last Time Service Announcement, Series 14, on plans for an improved system of universal clock time dissemination. A copy of this information is available if you have not received one. The changes, very briefly, have a high probability in excess of 95 percent to change the system of dissemination of UT. Presently this is being done by the "offset" clock time system, UTC. In the future it will operate without offset on the standard frequency.

As you recall, standard frequency in the so-called Systeme Internationale (S.I.), is defined by the length of one second expressed in so many cycles of the cesium frequency. The Observatory does not at this time correct its clocks or operate its clocks at this rate, but instead operates at a slightly different rate called "offset." Under that system, it has been able, with very few adjustments, to stay within 100 msecs of UT. The list, which has been shown before, indicates that a very large number of users require that kind of precision, and that has been the reason for the system of UTC as it has been operated until now.

The yearly frequency adjustment has not always been sufficient to retain the rate within the tolerance, and the Observatory has had to make additional 100-msec adjustments. However, they were very infrequent.

*Director, Time Service Division, U.S. Naval Observatory, Washington, D. C. (202) 254-4546.

That system was an excellent one; in fact, it was the perfect one 15 years, 10 years, or 5 years ago. But approximately 1,000 atomic frequency standards are now owned and operated by the U. S. government or by contractors; and many, many oscillators are working continuously in the field. The Observatory has been lucky during the last four years not to be forced to make any such frequency adjustments. However, that luck cannot be depended upon to prevail, and in the future such adjustments may be required every year or every second year. It has become quite evident that the great increase, or expected increase, in time-frequency technology users will force upon us a revision of these methods. Once you agree that the frequency offset is a bad thing and that it is very hard to change frequencies, for instance, of a TRANSIT satellite, of a TIMATION satellite, or of a listening station in Antarctica; and once you agree that one cannot continue to make frequency adjustments, then you must provide UTI by way of information in the form of a time code which will give you the small differences (which may become as large as .6 or .7 seconds) directly on the time signal. The code, which the Observatory intends to use on the Naval time signals (which are presently emitted on about 35 frequencies every couple of hours) will be in this form, which will indicate the digit in question by emphasizing or marking the respective second tick.

There are two questions with which as many potential users as possible should certainly be acquainted. If you have any opinions on them, let the Observatory staff hear them. The two questions are these: (1) Is there any need to have that correction immediately available at the moment of use, (with the time signal) with a precision exceeding 100 msecs; say 10 msecs? Some users have indicated that there may be such a requirement. If there is such a requirement, the Observatory wants to know about it. (2) Would the proposed time code be acceptable, and do you envision any difficulties? There is one which came to light after the announcement

was published, that it would be impossible to mark the zero digit. That point can be modified to the extent that if the correction is going to be zero, the mark will be second 30 or - 0, instead of + 0. UT is defined as a correction to be applied to UTC in order to give UT1 directly an additional change since the users are not interested in UT2. It is an artificial concept which is excellent for the timekeeping and timemeasuring people, but not for the user. The user needs UT1, and the correction, therefore, will refer directly to UT1. At any rate, if you plot that correction, you will have adjustments of exactly 1 second. When the adjustment begins to exceed -½ second, then it will jump to + ½ second. The correction will go slowly from + to -, and a step will be made about every year or so. That adjustment, therefore, will be exceedingly simple for all precision clocks. All that is necessary is to press the button at the right moment and you have dropped one second. It is the dropping of the second which will, in all likelihood, be a necessary adjustment--not the introduction of an additional second. However, the system makes provisions for both, because the performance of the earth's rotation cannot be predicted far enough into the future. So, that is the way the difference will go, and the advantage will definitely be that it is a better compromise which necessarily has to be selected. It is a compromise weighted more in favor of electronic timekeeping, of applications in physics and technology, and less in favor of the users of astronomical time.

The Observatory must move to that system because of almost insurmountable difficulties which otherwise would have occurred. However, as stated in the proposal, it will really have minimum impact on the users. It is only an adjustment which you will have to make on your clock, showing minutes and hours and days of the week, but not on your electronic systems for LORAN-C, for instance, nothing needs to be adjusted. All the Observatory will do is issue new times of coincidence tables (TOC) to become effective at the moment a step is going to be made, which will be known three or

for months in advance, and you will just remove the old table, throw it away, and use the new one. You need not make any adjustment except on your wall clock, The adjustment also will not disturb OMEGA. None of these systems needs to be adjusted. All that has to be done is to receive a new reference table to give you the fundamental epoch of the system. The same could be true, of course, for a collision avoidance system. Simply do not start on seconds 3,6,9 and so on, if your basic period is 3 seconds, but instead start on 1,4,7 and so on.

Everybody should now be aware of these plans and there does not seem to be any major difficulty from the correspondence which has been received in response to this announcement. A feeling of relief is evident from some people who said, "that is very fine; we didn't like the offset frequency and that is a step in the right direction."

CONCEPT AND ADVANTAGES FOR PTTI INTEGRATION OF TIME ORDERED SYSTEMS

by Dr. G.M.R. Winkler*

The question: To what degree is the Naval Observatory concerned with distribution of precise time to the lowest level of each individual user? This is really a question of policy and of basic decisions. It brings up, of course, the problem of fundamental distribution philosophy which will be answered in as much detail as possible.

The Observatory is in a period of transition. What it does now, of course, is not perfect. It sends traveling clocks to individual centers of activities--for example, to Oahu, where the Naval Astronautics Group operates a time reference station, Detachment Charlie (see Figure 1). This station also furnishes data for adjustments of more local time services. In other words, a concept of "trunk-line" timing is used.

This, of course, can only be considered an interim solution and it may even be considered an economical solution as long as there are only a few users, but it should not be the final one. One, therefore, has to ask what the concepts should be for the organization of PTTI distribution (see Figure 2).

First is the concept of <u>economy.</u> It appears unnecessary to have one specific system for the distribution of time, as long as so many systems are available which are capable of distributing time as a piggyback operation. This makes PTTI available on navigational or communication

*Director, Time Service Division, U.S. Naval Observatory, Washington, D.C. (202) 254-4546.

PRECISE TIME SYNCHRONIZATION SERVICE (PTSS)
WORLD DISSEMINATION

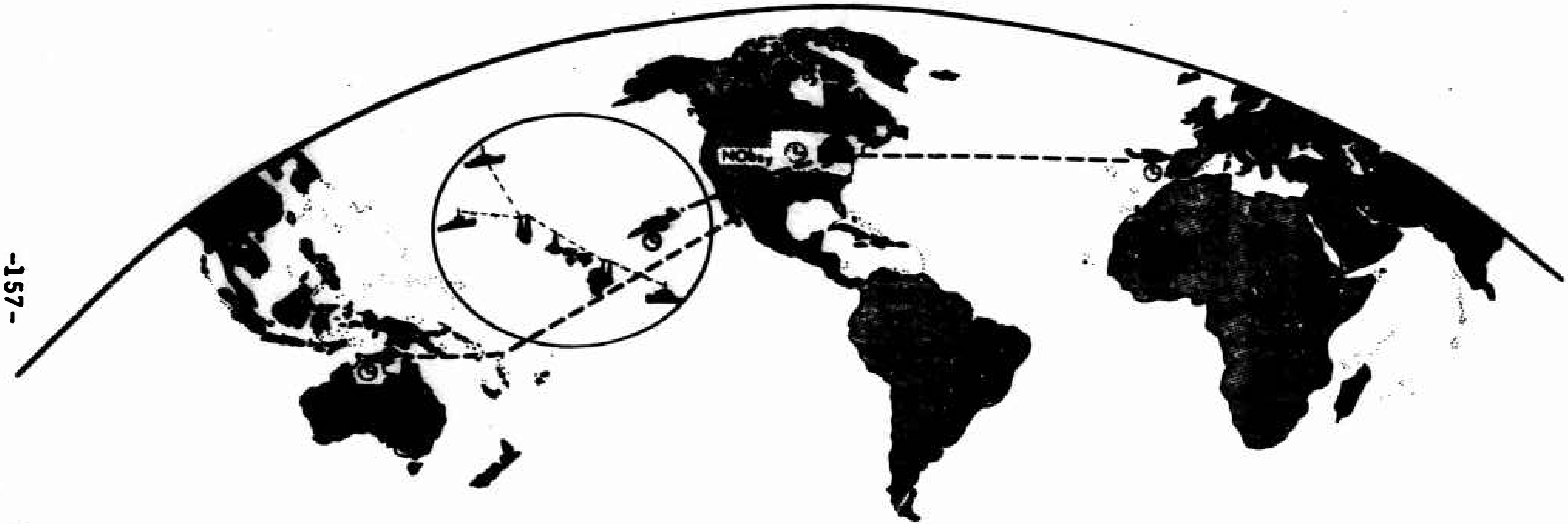


FIGURE 1

DISTRIBUTION

CONCEPTS

1. ECONOMY: SUPERPOSITION OF PTTI ON NAV & COMM. SYSTEMS
2. REDUNDANCY: USE DIFFERENT SYSTEMS, IF ECONOMICAL
3. ORGANIZATION: HIERARCHY — ONE SOURCE - "TRUNK LINE" TIMING TO PTRS

SPECIFICATION OF NEEDS

1. PRECISION OF SYNCRONIZATION
2. FREQUENCY OF ACCESS TO SYNCRONIZATION
3. QUALITY OF CLOCKS USED (RELIABILITY X PERFORMANCE)

WITHIN SERVICES: ARMY-NAVY-AF CALIBRATION SYSTEM

BY AREA: GLOBAL-INTERMEDIATE-LOCAL SERVICES

BY SYSTEM: PROPAGATION PTTI WITHIN EACH SYSTEM, INTERFACE WITH OTHERS AS BACK-UP

EXAMPLES

OMEGA USES INTERNAL SYNCH. AND USES LOR-C AS EXTERNAL BACK-UP

MANY LOR-C CHAINS CAN BE LINKED DIRECTLY, BUT MUST USE SATELLITES AND PORT. CLOCKS FOR CHECKING

FIGURE 2

systems. That principle is far superior to the design or implementation of a specific time distribution system, because it offers as a second benefit, the necessary redundancy. Different systems should be used simultaneously, since only incremental costs have to be spent to provide that additional service.

PTTI incremental cost is sometimes exceedingly small. To put time signals on the VLF high-powered transmitters requires an expenditure only for the clocks--an expenditure of approximately $30,000 or $40,000 per station, with some redundancy, compared to the millions of dollars of investment for the station itself. Redundancy will become more important in the future, since there are several time frequency systems under development, and these may require more reliable access to synchronization sources.

As to organization, Figure 2 in Mr. Stone's presentation (page 123) exploits the principle of hierarchy. There is one source--trunk-line timing to Precise Time Reference Stations (PTRS)--which provides the nodal points for regional distribution of time. For the specification of needs, precision of synchronization is only one parameter, and frequency of access is another very necessary parameter. The payoff to be decided is where to put the money, either in the quality of clocks or in the frequency of access to synchronization.

The overall principle of organization would be very simple if it were not for other complicating factors. There are calibration services within the Army, Navy, and very extensively in the Air Force. Evidently, needs for certification exist here which are in direct conflict to such an organization. In addition, there are geographical facts; there are systems which provide global synchronization or intermediate range or local services; and there is synchronization within each system. It would be a grave mistake for any system designer who proposes to use time frequency technology not to provide for some synchronization capability within the

system. In addition, however, it is necessary to provide for an interface to satisfy the requirements of redundancy and invulnerability against jamming or spoofing. Such an interface must be provided, therefore, with other systems as a backup. That appears to be the real crux of the whole concept of PTTI. There is no justification for going to more expensive clocks and less frequent access, if these considerations do not make a system less vulnerable and more reliable. (That is a point of greatest importance, not only for military systems, but also for any kind of civilian time frequency system.)

Figure 3 shows the capabilities of the standard transmitting stations. The high-frequency time signals are of continuing necessity. There are approximately 50 reliable time signal standard transmission stations distributed over the earth which are synchronized to about 1 msec. They all cooperate in the BIH system of coordinated time which has, at the present time, a tolerance of 1 msec. Within the United States or in the Eastern Pacific, one will listen to WWV, WWVH, and in addition, on the East Coast, the excellent Canadian time signal, CHU. From these stations, time is transmitted very reliably and very simply to 1 msec precision, or greater. The day-to-day variations of the WWV signals which we observed in Washington, D.C. are on the order of 0.2 msec, if the precaution is taken to make the same measurement, on the same frequency, at the same time every day. Any PTTI user should have access to a $50.00 communication receiver, and one must compare that kind of timing capability with other concepts which have previously been discussed.

The CIRR has consistently neglected to consider possible improvements in the high-frequency time signal emissions. These improvements cannot be incorporated because of the limitations to 5-kc bandwidth. If time signals were radiated in a bandwidth of 20 kc and the number of stations was reduced in favor of bandwidths, there would be a distribution

DISTRIBUTION

1. HF RADIO TIME SIGNALS: 1 ms GLOBAL
2. PORTABLE CLOCK: $\frac{1}{2}$ μs GLOBAL
3. VLF-OMEGA: 1-3 μs PHASE TRACK (RELATIVE)
4. LORAN-C: $\frac{1}{2}$ μs NORTHERN HEMISPHERE EXCEPT WESTERN U.S.
5. SATELLITES:

   A) DSCS: 0.1 μs "TRUNK LINE" — 2 WAY
   B) TACSAT: 0.5 μs "INTERMEDIATE" — 2 WAY
   C) TRANSIT: 10 μs GLOBAL — SILENT (ONE WAY)
   D) DNSS: 0.1 μs GLOBAL — SILENT (ONE WAY)

6. EXOTICS: R&D (VLBI, POWER LINES ETC)

   TV FOR LOCAL SERVICE

   UHF BEACONS: ——"——

   μ WAVE: LOCAL LINKS

FIGURE 3

system in which each mode of atmospheric propagation could be clearly distinguished by time of arrival. There would also be a stability of these modes either the same or nearly the same, as the skywave propagation of LORAN-C; namely, better than 50 μsecs. The stations could be reduced in number very easily, since some were built only for reasons of prestige. Some crowding may occur in the future when all the developing nations insist on a radio standard time system. To summarize, radio time signals will continue to be required by navigators as well as many others.

The exact opposite system with respect to numbers, costs, etc., is one which has already been mentioned--the portable clock. It is a system which has been called a counsel of despair, but it is one which can be implemented immediately. Inasmuch as there are only 100 to 200 users, it is still, by far, the most economical way to bring time to any location of the surface of the earth with better than one-half usec precision.

Many people propose $5 million or more for systems to satisfy five or ten users. Such expensive designs can no longer be considered. With regard to VLF or OMEGA, PTTI capability for a very small cost exists, and I am amazed that VLF seems to be completely out of fashion with many users.

Relative phase track can be performed today with great reliability without danger of loss of coherence, and it gives everyone located anywhere on earth a timing capability of a 5-μsec precision. The situation is different only by an order of magnitude from what there is in LORAN-C; the same thing will be true at OMEGA. The local setup must be calibrated to extract 1 μsec, because other effects enter. Antenna problems are not important for navigational applications, because differences are measured; however, for timing applications they are essential and may be a primary limitation. The LORAN-C is really the best existing operational distribution system with a capability exceeding 1 μsec. Unfortunately, it is not available everywhere.

With regard to satellites, the future situation may utilize the Defense Satellite Communication System and possibl TACSAT with a mutually compatible PTTI modem. This will yield a timing precision certainly in excess of 0.1 μsec, as referenced in the very conservative presentation by Mr. Stone and Mr. Murray. There was nothing in Mr. Murray's data to indicate that the present limit of performance is not entirely due to the limited resolution of the measurement equipment. The figure of 1 μsec is excellent for timing precision. The system will soon be in operation. The concept has been approved both by the Joint Chiefs and by DCA and efforts are well under way to provide an operational capability to the major centers of activity. Hawaii will, of course, be the first, with other stations to follow. The concept contains a link between the East Coast and the West Coast of the United States.

Of the next two systems--TRANSIT and TIMATION--the major advantage is the fact that they are "passive." TRANSIT is an existing capability which is not being exploited. There are five TRANSIT satellites in the air, and there are replacements scheduled in an operational way. It is a full-going system, and it will continue to operate for a long time. It is a pity that the TRANSIT capability has not been utilized for PTTI except by the French, who have demonstrated it very surprisingly.

There are "exotic" systems for PTTI which have been mentioned. But there are also at least 100 different navigational concepts for electronic navigation, and each one would be a useful concept for the dissemination of time.

The question appears to be not what <u>can</u> be done but what <u>should</u> be done. Where should the money be spent? Which compromise would be the best, both from the present point of view and for the foreseeable requirements? The use of television stations is of great importance wherever they are available for local dissemination of high-precision time.

Several concepts have been discussed in previous talks and should be reviewed briefly. The first one is the utilization of the television signals in a differential way. The differential system was first exercised and demonstrated by Tolman and has been used for a couple of years between major timing centers. It does not require any investment at all on the part of the television stations, not even a stabilized carrier emission. One just selects a pulse and makes differential measurements.

The second system, which is the present "line 16" system, or the one which was proposed and designed by Mr. Davis of the National Bureau of Standards, is one which would be of use for application as a local system for dissemination of time. With regard to the "network" dissemination, some essential additional comments are in order. Namely, that although it is true that microsecond stability from day to day over larger distances (almost continental distances) is available, it is also true that the service is continuously being interrupted. The same objection exists against the HF timing signal. That system should also be tested by the same standards and there may be an operational difficulty. More importantly, the propagation delay through the network from time to time changes violently.

There has been a proposal made by the Air Force, Newark, which has great merit, and which is outlined following this discussion. Briefly, they propose to use all three networks; however, people should not immediately jump into a sole reliance on this method because very serious difficulties could arise. At least, "caution" is a very good adjective here until more operational experience has been gained. The television system's great usefulness for local distribution would be of interest anywhere. Wherever there are centers of activity, there is a need for entertainment, and there will be entertainment stations not only in the

United States but in other areas as well. Such a system is very easy to set up and it offers terrific resolution at very little investment. The system has merit; however, the Observatory is faced with a dilemma, in view of some differences of attitude and interest between it and NBS, which evidently is interested in having a very wide general use of the system at a modest accuracy. The Observatory's interests are to use the system to the very highest possible precision in those areas of activity where there is the greatest demand.

This dilemma is posed because the Observatory still has to work out a design which would be compatible with both purposes, because otherwise, approval from the FCC will be difficult to obtain. The FCC, for very good reasons, has to move cautiously in its approval of any such system. Such compatible designs are possible and, such systems should be put into operation immediately. There is some danger that the common R&D syndrome to develop forever and to never become operational will prevail.

The Observatory is at the present time making an extensive effort to improve its own capabilities (see Figure 4). The improvements of the capabilities go on in every ar --in the provision of a very stable, very reliable time base and in the determination of astronomical time where a small improvement by a factor of two to five can be squeezed out. Some of these capabilities will not be of use in PTTI, but in related areas like polar variation, etc.

The greatest problem at the moment is to provide funding for high-precision synchronization of all LORAN-C chains, which means that direct synchronization will obviate the need to use corrections, as mentioned by Cdr. Potts. The program has been approved by the Secretary of Defense and is now in the reliable hands of the fiscal people where it will be solved. The next great interest and effort is in making use of the DSCS

PLANS

1. IMPROVEMENT OF USNO CAPABILITIES
2. HI-PREC. SYNCH. OF ALL LORAN-C
3. USE OF DSCS OPERATIONALLY FOR TRUNK-LINE TIMING TO PTRS
4. UTILIZATION OF FSK SYNCH ON <u>VLF</u>
5. OMEGA SYSTEM
6. USE OF DNSS PROTOTYPES
7. LINK-UP OF MAJOR USERS BY TV, μ WAVE, ETC.

FIGURE 4

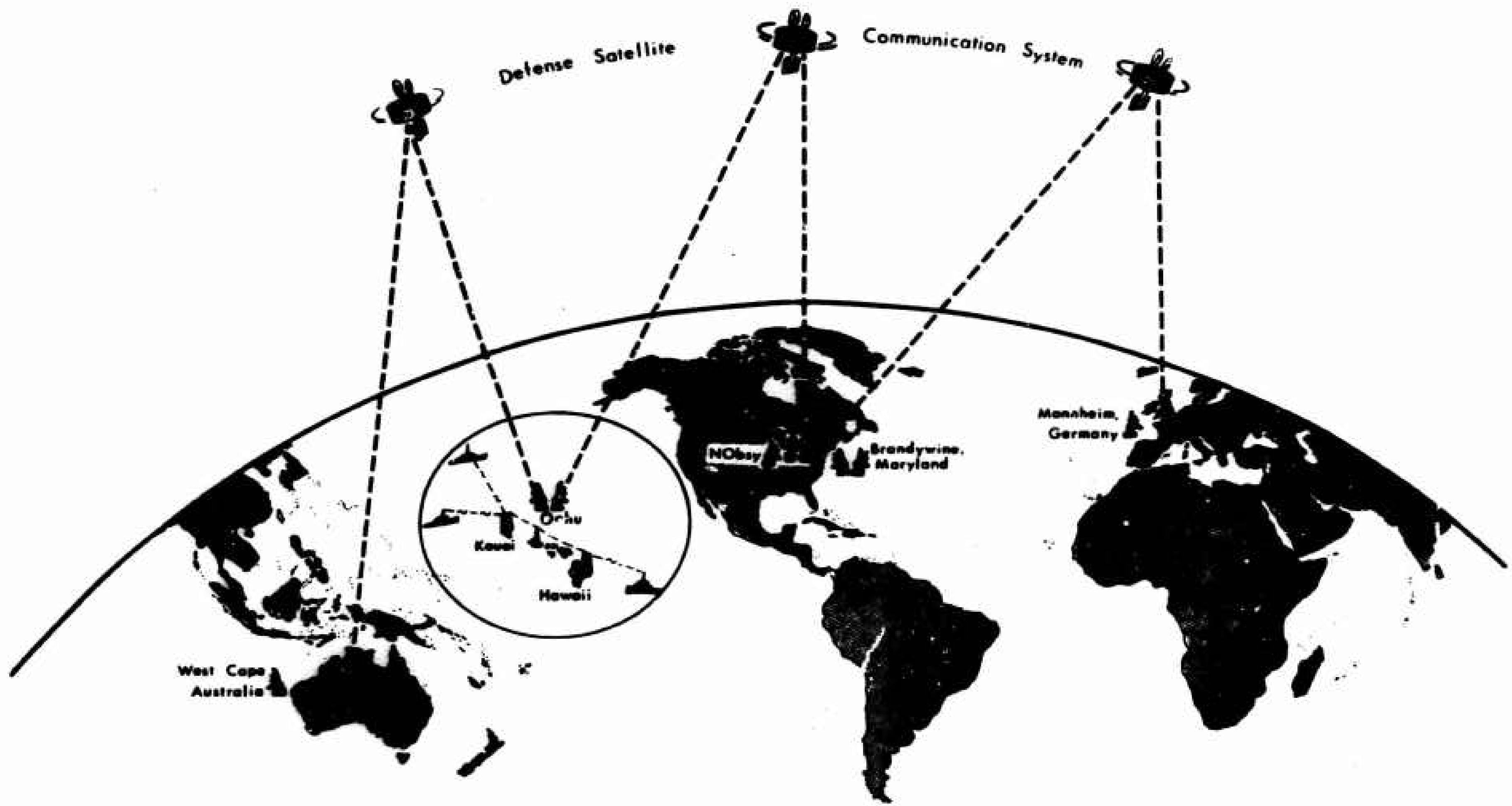
capabilities for trunk-line timing, not only with the precise time reference stations, but also with a number of additional stations--particularly in the Air Force where there is an interest to link-in with that system. It can be done, and there is general agreement that this is very desirable.

Another item of interest concerns the DNSS prototypes. TIMATION II can already be utilized for time purpose dissemination. The numbers which you have seen on the Alaskan LORAN chain frequencies are examples of what can be expected for operational use.

Finally, a point of concern is the link-up of major users by television or by microwave. If a hierarchical organization of time distribution is accepted as an overall strategy, there should be no serious objection for the reasons and the various principles which have been previously listed. But if that is accepted as a primary concept, then it is clear that access possibilities should be provided to regional or local sources of synchronization while more detailed requirements and their justifications should be left to the user or the user system. The Observatory does not have the capability to even consider organizational details; however, it should know about problems and such requirements.

Most people, and particularly those good system designers who have kept in mind the principle that each PTTI system must provide internal synchronization, evidently feel that this is what they need; they have provided for all of their needs and they see no benefit in interfacing with anyone else. That question points to an identity crisis within the PTTI community, because where and why does the need exist to single out this field of interest activities and coordination efforts? How far should we go, and what are the main benefits? They simply have to do with hardening operations of all systems and with economy of operation.

Figure 5 shows the new, high precision "trunk-line" distribution system. For the immediate future, the Observatory will replace a great number of portable clock trips to major centers by satellite links.



PRECISE TIME AND TIME INTERVAL (PTTI) – WORLD DISSEMINATION

FIGURE 5

APPENDIX A

CONFERENCE AGENDA

AGENDA FOR
DOD PRECISE TIME AND TIME INTERVAL (PTTI)
STRATEGIC PLANNING MEETING

10 December 1970

0900-0915	WELCOME Dr. L. B. Wetzel Superintendent, Communications Science Division Naval Research Laboratory
0915-0930	INTRODUCTION Captain John R. Hankey, USN Superintendent U. S. Naval Observatory
0930-0945	ADMINISTRATIVE NOTES

TECHNICAL PROGRAMS

PRECISE TIME AND TIME INTERVAL VIA:

0945-1015	VLF Mr. Robert Stone Head, Radio Frequency and Time Section Naval Research Laboratory
1015-1045	OMEGA NAVIGATION SYSTEM Mr. L. A. Fletcher Assistant Project Manager for Electronics (PME-119) Naval Electronic Systems Command
1045-1115	LORAN "C" NAVIGATION SYSTEM Lieutenant Commander C. E. Potts, USCG Electronics Engineering Division U. S. Coast Guard Headquarters
1115-1145	SATELLITE COMMUNICATIONS SYSTEM Mr. J. A. Murray Radio Time and Frequency Section Naval Research Laboratory

1145-1215	TACTICAL SATELLITE SYSTEM Mr. George Kamas Time and Frequency Division National Bureau of Standards
1245-1345	LUNCH
1345-1415	621B SATELLITE SYSTEM Lieutenant Colonel J. A. Fiebelkorn Project Officer, Policy and Plans Group U. S. Air Force Headquarters
1415-1445	TRANSIT NAVIGATION SATELLITE Mr. Lauren Rueger NAVSAT Project Scientist Applied Physics Laboratory
1445-1515	TIMATION NAVIGATION SATELLITE Mr. Roger L. Easton Research Engineer, Space Technology Division Naval Research Laboratory
1515-1545	MOON BOUNCE Dr. Walter H. Higa Technical Staff, Telecommunications Division Jet Propulsion Laboratory
1545-1615	NETWORK AND LOCAL TELEVISION Mr. George Kamas Time and Frequency Division National Bureau of Standards
1615-1645	MICROWAVE, OPTICS, LASERS, AND OTHER EXOTIC SYSTEMS Mr. Robert Stone Head, Radio Time and Frequency Section Naval Research Laboratory

MEETING AGENDA

11 December 1970

0900-0915	ADMINISTRATIVE NOTES
0915-0930	REQUIREMENTS AND PERFORMANCE FOR TODAY'S ATOMIC STANDARDS Dr. G. M. R. Winkler Director, Time Service Division U. S. Naval Observatory
0930-1000	DISCUSSION
1000-1015	EXPLANATION AND REQUIREMENTS FOR UNIVERSAL TIME Dr. G. M. R. Winkler
1015-1030	CONCEPT AND ADVANTAGES FOR PTTI INTEGRATION OF TIME ORDERED SYSTEMS Dr. G. M. R. Winkler
1030-1100	DISCUSSION
1100-1145	PTTI REQUIREMENTS, SERVICES, AND RECOMMENDATIONS Dr. G. M. R. Winkler
1145-1245	DISCUSSION
1245-1345	LUNCH
1345-1445	PTTI DISSEMINATION SYSTEMS DEMONSTRATIONS
1445-1500	CLOSING REMARKS
1500	ADJOURN

APPENDIX B

LIST OF PARTICIPANTS

DOD PRECISE TIME AND TIME INTERVAL (PTTI)
STRATEGIC PLANNING MEETING 10-11 December 1970

LIST OF ATTENDEES

Name	Activity	Code	Address	Tel. No.
Ackerman, K.	NAVOCEANO		Washington, D.C.	(202)763-1270
Acrivos, H.N.	NObsy		Washington, D.C.	(202)254-4587
Anderson, Neil P.	Hq ESD/XRC		Bedford, Mass.	(617)271-3838
Andrews, D.	NRL	5418	Washington, D.C.	(202)767-2285
Applebaum, L.T.	ACIC		St. Louis, Mo.	(314)268-1000
Atwood, R. LCDR	NObsy		Washington, D.C.	(202)254-4597
Bailey, S.	NRL	5424C	Washington, D.C.	(202)767-3654
Barnaba, J.F.	AGMC		Newark, Ohio	(614)344-2171
Bartholomew, C.	NRL	5162	Washington, D.C.	(202)767-2595
Batie, H. LCDR	CNO	094E2	Washington, D.C.	(202)697-4441
Beard, R.	NRL		Washington, D.C.	
Beck, H.	NRL	5418	Washington, D.C.	(202)767-2285
Behen, T.R.	COMNAVCOM		Washington, D.C.	(202)896-0820
Berg, W.	NRL	5424C	Washington, D.C.	(202)767-3654
Bigelow, H.	OSD (OATSD(T))		Washington, D.C.	(202)697-6820
Bittel, R.H.	DCA		Reston, Va.	(703)437-5272
Blocker, L.	NRL		Washington, D.C.	
Bowman, J.	NRL	5424	Washington, D.C.	(202)767-2661
Boyd, R.	NObsy		Washington, D.C.	(202)254-4554
Breetz, L.D.	NRL	5167	Washington, D.C.	(202)767-2595
Bright, Duane	NAVOCEANO	7130	Washington, D.C.	(202)767-2875
Buss, H.	NRL		Washington, D.C.	
Buhl, H.J.	NAVSEC	05614	Arlington, Va.	(703)692-8488
Caldwell, C.L.	NAVSEC	6181D	Hyattsville, Md.	(301)436-1571
Caldwell, R. Maj.	OAC-SCE	CECS-4A	Washington, D.C.	(202)695-3217
Calenda, F. MSGT	AFTAC		Alexandria, Va.	(703)695-1226
Chi, Andrew	NASA/GSFC	521	Greenbelt, Md.	(301)982-5611
Clements, David LT	USCG		Alexandria, Va.	(703)971-1600
Cole, R.	NRL	5458	Washington, D.C.	(202)767-2265x46
Cook, Robert P.	NAVAIR	05F	Washington, D.C.	(202)693-2410
Craig, A.	NRL	5424	Washington, D.C.	(202)767-3654
Crippe, E.R.	NELC		San Diego, Cal.	(714)952-6714
Davis, C.B.	NRL	5410	Washington, D.C.	(202)767-3469
Davis, J.H.	NObsy		Washington, D.C.	(202)254-4577
Davis, Wayne E.	NELC	2100	San Diego, Cal.	(714)225-6783
Dermody, R. CDR.	NObsy		Washington, D.C.	(202)254-4474
Dix, William H.	DCA	340	Washington, D.C.	(202)694-2191
Easton, Roger L.	NRL	5160	Washington, D.C.	(202)767-2595
Ehrlich, E.	Hq NASA		Washington, D.C.	(202)962-2388
Eisenberg, R.L.	NRL	5423	Washington, D.C.	(202)767-3544
Eversole, B.C. LT.	NOS	C13	Rockville, Md.	(301)496-3786
Farr, Edwin H.	DOT		Cambridge, Mass.	(617)494-2020
Fey, R. Lowell	NBS		Boulder, Colo.	(303)447-1000x3295
Fiorelli, M. COL.	USASTRATCOM		Ft. Huachuca, Ariz.	(602)538-2151
Fiebelkorn, J.A., LTCOL.	USAF Hdq.		Washington, D.C.	(202)695-4062
Fletcher, J.	NRL		Washington, D.C.	
Fletcher, L.A.	NAVELEX	PME-119	Washington, D.C.	(202)692-8779
Fosque, H.S.	NASA	TS	Washington, D.C.	(202)962-0126
Galejs, J. Dr.	NRL		Washington, D.C.	
Gillette, P.	Stanford Res.		Menlo Park, Cal.	(415)326-6200
Gattis, T.	NRL	5424B	Washington, D.C.	(202)767-2347
Gilchrist, C.	DIAM		Washington, D.C.	(202)697-3020
Gleason, R.	NRL		Washington, D.C	
Goring, Walter	NAVELEX	033	Washington, D.C	(202)692-6416
Green, Robert	NRL		Washington, D.C.	

Name	Activity	Code	Address	Tel. No.
Hafner, E.	US Army Elect. Cmd.		Ft. Monmouth, N.J.	(202)535-1878
Hager, E.P. CAPT.	AFTAC		Alexandria, Va.	(703)695-1226
Hall, R.	NObsy		Washington, D.C.	(202)254-4547
Hankey, J. CAPT.	NObsy		Washington, D.C.	(202)254-4564
Hashimoto, R. MAJ.	USAF Hqts.		Washington, D.C.	(202)695-7461
Haupt, R.R.	NObsy		Washington, D C.	(202)254-4598
Hedgespeth, R. CAPT	USAF		F.E.Warren AFB, Wyo.	(307)775-2866
Heidig, W.R.	NAVELEX	05613	Washington, D.C.	(202)696-4793
Hennessy, J.	NRL		Washington, D.C.	
Herman, J.	Stanford Res.		Menlo Park, Cal.	(415)326-6200
Herring, J. MAJ.	AFCRL		Bedford, Mass.	(617)861-3655
Hickey, C. B.	USCG		Alexandria, Va.	(703)971-1600x46/77
Higa, W.H.	JPL		Pasadena, Cal.	(213)354-4240
Himes, D.	NRL	5420	Washington, D.C.	
Hortman, J.	NRL		Washington, D.C.	
Holman, W.	NELC		San Diego, Cal.	(714)225-7064
Hovey, J.M.	NRL	5262	Washington, D.C.	(202)767-2814
Howell, W.R.	OAC-SCE		Washington, D.C.	(202)693-6930
Hughes, J.A.	NObsy		Washington, D.C.	(202)254-4590
Inglis, W.	ONR		Washington, D.C.	(202)692-4217
Irby, R.E.	RSC Inc.		Washington, D.C.	(202)659-1867
James, R.E.	SAMTEC		Vandenberg AFB, Cal.	(805)865-5117
Jensen, R.S. CDR	NELEX	EP04	Washington, D.C.	(202)692-8280
Jones, D.	NRL		Washington, D.C.	(202)767-3166
Kamas, G.	NBS	273.01	Boulder, Colo.	( )447-1000x3378
Katz, J.	SSPO	Sp-24	Washington, D.C.	(202)696-4271
Kaufman, D. C.	NASA/GSFC		Greenbelt, Md	(301)982-5595
Kelly, F.	NRL	5461	Washington, D.C.	
Klock, B.L.	NObsy		Washington, D.C.	(202)254-4583
Knipling, L.	DIAMC		Washington, D.C.	(202)697-3450
Kralovec, I.J.	DCA		Washington, D.C.	(202)694-2470
Kronlund, K. LTCOL	ESD		L.G. Hanscom, Mass.	(617)861-5111
Kugel, C.	NELC		San Diego, Cal.	(714)225-7137
Kulikowski, E.	NRL		Washington, D.C.	
Kline, E.L.	NRL		Washington, D.C.	
Laios, S.	NASA/GSFC	573	Greenbelt, Md.	
Lamar, U. LCDR	SSPO/NELEX		Washington, D.C.	(202)696-4271
Lavanceau, J.	NObsy		Washington, D.C.	(202)254-4548
Le Fande, R.A.	NRL		Washington, D.C.	
Lieberman, T.	NAVELEX		Washington, D.C.	(202)692-7375
Lynch, D.	NRL		Washington, D.C.	
Lord, J.	NSA		Ft. Meade, Md.	(301)688-6506
Luther, C.A.	NELEX	EP04	Washington, D.C.	(202)692-8281
Mancini, A. Dr.	USA TOPO LAB.		Ft. Belvoir, Va.	
Marshall, R.L.	NESC		Washington, D.C.	(202)692-3951
Martin, C.F. Dr.	ACIC		St. Louis, Mo.	(314)268-4112
Mazur, W.E.	NASA/GSFS			
McClure, D.L.	DCA		Washington, D.C.	(202)694-3501
McConnell, V.	NSA		Fort Meade, Md.	(301)688-7534
McCrumb, J.B.	NAVMAT Command		Washington, D.C.	(202)692-2144
McCurry, P.C.	USCG		Alexandria, Va.	(703)971-1600x46
McIntire, O.	FAA		Washington, D.C.	(202)426-8576
McKendry, N.	OAC-SCE		Washington, D.C.	(202)695-3275
McLaughlin, D.E.	NRL		Washington, D.C.	
Meredith, E.	NRL		Washington, D.C.	
Michelini, R.D.	Smithsonian Astrophysical Observatory		Cambridge, Mass.	(617)864-7910 X 491

Name	Activity	Code	Address	Tel. No.
Mirachi, C.	NRL		Washington, D.C.	
Mohr, J.L.	McDonnell Douglas		St. Louis, Mo.	(314)232-5327
Moore, S.E.	NAVELEX	0512	Washington, D.C.	(202)692-7324/5
Murphy, H.	NRL	5424	Washington, D.C.	(202)767-3654
Murray, J.	NRL	5424	Washington, D.C.	(202)767-3309
Neumann, G.W.	NSSC	03526	Washington, D.C.	(202)692-1175
Nuber, G.E.	RSC Ind.		Washington, D.C.	(202)659-1867
O'Neill, J.	NRL	54246	Washington, D.C.	(202)767-3309
Osborne, E.	JHU/APL		Silver Spring, Md.	(202)953-7100x2628
Outlaw, D.M.	NAV OBSERV		Washington, D.C.	(202)254-4486
Parsons, P.	NSA		Ft. Meade, Md.	(301)688-6506
Parker, C.V.	NRL	5260	Washington, D.C.	(202)767-3396
Pendleton, F.L.	DCA		Washington, D.C.	(202)694-2470
Perfetto, H.	RSC IND.		Washington, D.C.	(202)659-1867
Peterkin, E.	NRL	5103	Washington, D.C.	(202)767-2891
Peterson, D.A. LTCOL	JCS		Washington, D.C.	
Petit, R. LT	NRL	5420P	Washington, D.C.	(202)767-2347
Phillips, D.	NRL	5424C	Washington, D.C.	(202)767-2061
Phillips, R.	NRL	5424C	Washington, D.C.	(202)767-2061
Poling, A.	ESSA		Rockville, Md.	(202)496-8620
Potts, C.E. LCDR	USCG	EEE/63	Washington, D.C.	(202)426-1193
Prast, J.	Sierra Res Corp		Buffalo, N.Y.	
Pritt, D.	NRL	5424D	Washington, D.C.	(202)767-3309
Rall, G.	NASA/GSFC	822.4	Greenbelt, Md.	(301)982-5706
Raudenbush, J.E.	NRL	5466	Washington, D.C.	(202)767-2761
Reder, F. Dr.	USAECOM		Ft. Monmouth, N.J.	(609)535-1624
Rich, C. Capt.	JCS	J-6	Washington, D.C.	(202)697-0679
Rickey, E.	MLC AGMC		Newark, Ohio	(614)344-2171
Robatino, V.G.	USA Satellite Comm		Fort Monmouth, N.J.	(201)532-2832
Rosenberg, J.	Hq NASA		Washington, D.C.	(202)963-3361
Rohde, F.W.	USA Topographic		Washington, D.C.	(202)664-6728
Rueger, Lauren	JHU/APL		Silver Spring, Md.	(202)953-7100x378
Savarese, R.	NAVELEX	0561	Washington, D.C.	(202)692-8362
Schmid, J.	ENDS		Vandenberg AFB, Ca.	(805)866-4871
Scott, W.	Sierra Res Corp		Buffalo, N.Y.	(716)632-8823
Scull, D.	NAVOCEANO	3120	Washington, D.C.	(202)763-1534
Seeley, H.	CNO	OP35161	Washington, D.C.	(202)697-9376
Shostak, A.	ONR		Washington, D.C.	(202)692-4216
Sievers, W.	NRL	5351	Washington, D.C.	(202)767-2213
Smith, W.	NRL			
Sober, D.G.	NAVOCEANO	6320C	Washington, D.C.	(202)693-3845
Sonneman, H.	Spec Asst ASN		Washington, D.C.	(202)697-2045
Spencer, S.W.	Dept Army		Alexandria, Va.	(202)274-0430
Stetina, F. L.	NASA/GSFC	553	Washington, D.C.	(202)982-2357
Stone, R.	NRL	5424	Washington, D.C.	(202)767-3454
Stout, C.C.	NEXEX	PME-119	Washington, D.C.	(202)682-8779
Strand, K.A.G.	NObsy		Washington, D.C.	(202)254-4539
Strucker, P.	NAVPRO		Pomona, Cal.	(714)629-5111
Sumney, L.W.	NRL	5262A	Washington, D.C.	
Suttle, R.V.	NAVOBSERV		Washington, D.C.	
Swanson, E.	NELC		San Diego, Cal.	(714)225-6365
Swartwood, W.	NAVOCEANO		Washington, D.C.	(202)695-1415
Tomkinson, M. MSGT	AFTAC		Alexandria, Va.	
Tuttle, R.	NRL	5403	Washington, D.C.	(202)767-2054x539
Usilton, R.	NAVELEX	0514	Washington, D.C.	(202)692-7375
Varnum, F.	USATOPOCOM		Washington, D.C.	(202)986-2120

Name	Activity	Code	Address	Tel. No.
Venn, D.A.	NRL	5422	Washington, D.C.	(202)767-2441
Walls, D. M.	NASA/GSFC	832.2	Greenbelt, Md.	(202)982-5381
Webb, M.	NRL	5422	Washington, D.C.	(202)767-3563
Wetzel, L. Dr.	NRL	5400	Washington, D.C.	(202)767-3417
Wieder, B.	Dept Commerce	R611	Boulder, Colorado	(303)447-1000 x3881
Williams, M.F.	NRL	5432	Washington, D.C.	(202)767-3544
Wilson, F.	USATOPOCOM		Washington, D.C.	(202)986-2440
Winkler, G.	NObsy		Washington, D.C.	(202)254-4843
Wood, D.	NSA		Ft. Meade, Md.	(301)688-6506
Woodward, W. LTC	JCS	J-6	Washington, D.C.	(202)697-0679
Yaeger, J.A.	C&GS		Rockville, Md.	(202)656-8305
Zirm, R.	NRL	5164	Washington, D.C.	(202)767-2595
Zufall, S.	NASA/GSFC		Greenbelt, Md.	(202)982-5528